AN INVESTIGATION OF WINTER SENSIBLE HEAT FLUXES OVER LAC ST. LOUIS, MONTRÉAL, QUÉBEC, USING AN EDDY CORRELATION TECHNIQUE

by

Lisa Marie Kellman

Department of Geography
McGill University
August 1992

A Thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements of the degree of Master of Science.

Winter sensible heat flux measurements over Lac St. Louis, Montreal, Quebec

ABSTRACT

Sensible heat flux measurements were obtained over a shallow freshwater body through the late fall and winter period of 1991/92 in order to investigate the effect of meteorological conditions and ice coverage on the magnitude and direction of the sensible heat fluxes, and to evaluate an eddy correlation system as a means of conducting sensible heat flux measurements at remote sites under winter conditions.

Results suggest that the response of shallow water bodies to changes in meteorological conditions (particularly air temperature) is rapid, and that the direction and particularly the magnitude of the fluxes is mainly a function of the short term air temperature record. The sensible heat fluxes were found to decrease in magnitude with the formation of an ice cover; the maximum recorded fluxes prior to freeze-up being on the order of 120 W m^{-2}, whereas the maximum recorded fluxes shortly following formation of a complete thin (< 20 cm) ice cover being on the order of 45 W m^{-2}. This study suggests that the eddy correlation system has significant potential for winter applications. However, thermocouple breakages due to precipitation events suggest that further development of the system is required for long-term, remote site investigations.

RÉSUMÉ

Les mesures de fluctuations de chaleur sensible ont été obtenus d'une masse d'eau douce peu profonde durant la période de fin d'automne et de l'hiver 1991/92, pour rechercher l'effet des conditions météorologiques et de la couverture de glace sur l'empleur et direction des fluctuations de chaleur sensible, et pour évaluer un systeme de corrélation de tourbillon comme moyen de conduction des mesures de fluctuations de chaleur sensible de sites éloignés sous des conditions hivernales.

Les résultats suggèrent que la réponse des masses d'eau douce peu profonde aux changements de conditions météorologiques (particulièrement la température de l'air) est rapide et que la direction et particulièrement l'empleur des fluctuations est surtout une fonction de l'enregistrement de la température de l'air à court terme. On a trouvé que les fluctuations de chaleur sensible diminuent en empleur avec la formation d'une couverture de glace; les enregistrements maximum de fluctuations avant la gelée furent de l'ordre de 120 W m^{-2} , alors que les enregistrements de fluctuations maximum tôt aprés la formation d'une couche de glace minces (< 20 cm) complète, furent de l'ordre de 45 W m^{-2}. Cette étude suggère que le système de corrélation de tourbillon a un potentiel significatif pour les applications hivernales. Cependant les cassures thermocouple duent aux évènements de précipitation suggèrent que des développements plus avancés du système sont requis pour des recherches à long termes des emplacements éloignés.

Acknowledgements

I would like to thank all the people who helped me throughout the course of my studies at McGill. First I would like to thank my supervisor Ian McKendry for his help, and both Ian McKendry and John Lewis for financial support during the summer of 1991. Many people helped make my research easier including: the Point Claire Yacht Club for allowing installation of the instruments over the fall and winter season, Pete Lafleur for suggestions regarding equipment, Tom Meredith for his canoe, Tim Moore and Andrew Heyes for use of the truck, Paula for helping order equipment, Peter Barry for accompanying me out to the field on numerous occasions, and Bobby Downs for collecting equipment. I'd like to give a special thanks to Neil Comer for his help on numerous technical matters and for his accompaniment on many trips out to the field. Finally, I'd like to thank my mother for translating of my abstract, and my father for his support throughout the two years. Besos to Hugo for his help.

Lisa

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

An examination of turbulent fluxes over the Earth's surface provides a measure of the energy exchange between this surface and the overlying atmosphere. The measurement of turbulent fluxes on various temporal and spatial scales is an important component of contemporary climatological investigations, and the use of eddy correlation as the measurement technique increasingly widespread. Understanding of energy partitioning on a variety of temporal and spatial scales has important implications, including: 1) diagnostic studies of heat transport, cloud forcing and radiative heating, 2) specification of boundary conditions for GCMs (General Circulation Models), 3) improvement of parameterizations for sub-grid processes in GCMs, 4) validation of climate models, and 5) determination of long term trends (Breon and Gautier, 1990).

Canada has a large expanse of water bodies (particularly in the form of lakes) and as such there is significant potential for heat storage and subsequent heat release by these water bodies.

The purpose of this study is twofold. It's primary objective is to investigate the effect of meteorological conditions and ice coverage on the magnitude and direction of sensible heat fluxes over Lac St. Louis through the period of freeze-up until mid-winter.

Secondly, it is an evaluation of an eddy correlation system in such environments.

Although sensible heat flux measurements over freshwater have been few, there has been some fairly extensive work done in polar areas (Allison et al., 1982; Andreas et al., 1982; Allison and Akerman, 1980; Andreas, 1980; Andreas et al., 1979; Allison, 1973), which indicate a clear dampening of the fluxes with the formation of an ice cover. In these areas, the magnitude of the fluxes tends to be lowered significantly with ice cover formation, however fluxes tend to maintain fairly constant values under a given set of ice cover conditions once these conditions have stabilized. Over relatively shallow freshwater lakes, on the other hand, there is a smaller volume of water, and hence less potential for heat storage which makes the rate at which the water body loses heat and responds to meteorological controls such as air temperature an interesting study.

By setting up a measurement site on the shore of the lake, and examining only those sensible heat fluxes which originate from over this lake, it was hoped that a set of sensible heat fluxes representative of the various lake surface conditions could be obtained.

Only sensible heat fluxes were measured in this study, as it was anticipated that the latent heat flux would be quite small in terms of magnitude, and without very sensitive (and thus expensive) instruments, not worth measuring.

This study employs the use of a robust eddy correlation system to measure the sensible heat fluxes. It is therefore in part an evaluation of the use of this instrument system under fall and winter conditions in the vicinity of a temperate freshwater lake. This is important as eddy correlation is a much more accurate method by which to estimate the sensible heat flux than the common aerodynamic approach, an important consideration, particularly during the winter when the fluxes are strongly dampened. The system used lends itself well to longterm studies as it is relatively inexpensive and easy to maintain.

This thesis will be organized as follows. Chapter two will provide a review of the literature relating to the boundary layer, eddy correlation instrumentation, and the measurement of turbulent fluxes. As well, it will include an overview of the characteristics of fresh water bodies under the conditions generally encountered in the fall and winter (ie open water, ice cover, snow cover on ice, etc.). Chapter three will provide a general description of the site at which the study was conducted, and a discussion of the criteria in terms of selection of wind directions representative of over-water or over-ice flow. The second part of this chapter will review the instrumentation used in the study, not only the types, but their placement, the collection and processing of the data on the dataloggers, a discussion of the errors associated with the instrumentation used, and a brief description of trial runs with the eddy correlation instrumentation prior to installation at the measurement site.

Chapters four and five will discuss the results. Chapter four examines the representativeness of the 1991/92 winter in terms of air temperature, wind speed and direction, precipitation, and the effect of these meteorological conditions on the ice and snow cover. As well, it will provide a discussion of the performance of the instrumentation and make recommendations on the use of this instrumentation system under the conditions encountered in the study. Chapter five will examine the sensible heat flux record over the entire measurement period, and provide a detailed examination of a number of 24 hour periods representative of the various meteorological or source area conditions.

Finally, Chapter six will conclude with a summary of the instrumentation, an overview of the sensible heat fluxes and general meteorological conditions over Lac St. Louis, and recommendations for future research.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Boundary Layer

The boundary layer can be defined as "that part of the troposphere that is directly influenced by the presence of the Earth's surface and responds to surface forcings with a timescale of about an hour or less" (Stull, 1988). This atmospheric layer is of critical importance in climatological studies as it is within this layer that transfers of heat moisture and momentum occur between the Earth's surface and the atmosphere. These transfers are largely dependent on wind speed. When air is still, most fluxes occur by molecular diffusion and convection. However, as wind speeds increase, the fluxes increase. This results in a constant and relatively uniform mixing of the air layer in contact with the surface. The boundary layer depth varies daily (mainly in response to the cycle of incoming solar radiation), with daytime depths of 1 to 2 km and nighttime depths of as low as 100 meters (Panofsky and Dutton, 1984; Oke, 1987). Within the boundary layer, and in direct contact with the Earth's surface, exists a "constant flux layer" or "turbulent surface layer" in which the air is vertically homogeneous (Male and Granger, 1981; Oke, 1987). This surface layer is generally made up of the lowest 10%

of the boundary layer and thus may vary in depth from 10 m (at night with low winds) to 100 m (during the day with strong winds) (Panofsky and Dutton, 1984). It is within this constant flux layer that an estimate of the magnitude and direction of transfers between the Earth's surface and the overlying atmosphere can be obtained. Thus under assumptions of an homogeneous surface, measurements made anywhere in this layer at a given point in time are considered representative of the entire layer.

2.2 Methods of Flux Measurements

There are essentially two methods by which fluxes can be measured in the boundary layer: direct and indirect methods. Direct measurements of fluxes involves the deployment of instruments, at a single measurement level, that respond quickly enough to enable sampling of the individual eddies as they pass by the sensor. Indirect measurements on the other hand, require more than one measurement level for a given set of instruments and are based on a number of assumptions concerning the atmospheric conditions. There are numerous advantages and disadvantages associated with each method which must be considered when implementing a study. The following will briefly review the common indirect method, the 'profile' method, as well as the direct method used for this study, that of 'eddy correlation'.

2.2.1 Profile Method

The commonly used profile method, or the 'aerodynamic approach', requires the measurement of various atmospheric variables at more than one measurement level, so as to enable calculation of the change in a given variable with the change in height. It is limited because it makes assumptions about the wind profile and hence the atmospheric conditions and transfer coefficients. The standard gradient flux equations include the following:

Momentum	$\Gamma = \rho K_m du/dz$	(1)
Sensible Heat	$Q_h = \rho C_p K_n dT/dz$	(2)
Latent Heat	$Q_e = -\rho L_v K_e dq/dz$	(3)

where ρ and C_p are the density and specific heat or air respectively, L_v the latent heat of vaporization, K_m, K_n and K_e the turbulent transfer coefficients for momentum, heat and water vapour respectively, u the wind speed, z the height, T the temperature, and q the humidity.

Assumptions made in uncorrected flux measurements include a similarity in the transfer coefficients, and neutral stability. There are numerous corrections for other conditions of atmospheric stability (Swinback, 1968; Dyer and Hicks, 1970; Businger et al., 1971; Granger and Male, 1978; Male and Granger, 1981). The assumptions made can potentially yield numerous inaccurate results (Maykut, 1986; McBean, 1986; Oke, 1987), particularly with respect to the transfer coefficients in non-neutral conditions (Kondo et al., 1978). Even under non-neutral conditions, there exists debate as to the magnitude of von Karman's constant, k. Male and Granger (1981) point to a traditional k value of 0.4, and Businger et al (1971) find a k value of 0.35..

This method of measurement had advantages because it is relatively inexpensive, the instruments are quite robust, and as a result, it is useful for long term studies and studies conducted at remote sites.

2.2.2 Eddy Correlation

Eddy correlation is the most accurate method of flux measurement as it involves direct sampling of the eddies themselves as they pass the sensor. It requires taking a series of measurements of the relevant variables (depending upon the flux sought these variables may include the horizontal wind speed, u, the vertical wind speed, w, the temperature , T, and the humidity, q), and the division of the series into a mean and a fluctuating component. That is, a given variable X can be broken down such that $X = \overline{X} + X'$, where the $\overline{X}$ is the mean part of X and the X' is the fluctuating part of X. These fluctuations can then be input into the standard eddy correlation equations which include (Oke, 1987):

Momentum $$\Gamma = -\rho\, \overline{u'w'} \tag{4}$$

Sensible Heat $$Q_h = \rho\, C_p\, \overline{w'T'} \tag{5}$$

Latent Heat $$Q_e = L_v \overline{q'w'} \qquad (6)$$

where the overbar indicates the average of the sum of the instantaneous fluxes.

Figure 1 illustrates how the average of the instantaneous fluxes changes with changes in stability, using the example of the sensible heat flux (w'T') component. Under stable conditions (when the air temperature increases with height) sampling of the upwards moving side of an eddy will produce a positive w' value (air is moving upwards) and a negative T' value (as cooler air is moving up into warmer air) resulting in a negative w'T' value and hence a downward flux. Sampling of the downwards moving side of the same eddy will also produce a negative w'T' (and a downwards flux) as the w' value will be negative (air is moving downwards) and the T' value will be positive (as warmer air moves down into cooler air). Unstable conditions on the other hand, (in which the air temperature decreases with height) will result in a positive w'T' and upward fluxes as the upward moving air in an eddy will carry warmer air up and result in a positive T', and the downward moving air will carry cooler air down and result in a negative T'. The w' values will be the same as outlined above in the stable case. Therefore, regardless of whether the upwards or downwards movement of a particular eddy is being sampled, the w'T' will be the same sign.

Typically, the standard climatological procedure is to sample at a rate of 5 to 10 Hz (Amiro et al., 1988). The periods of time over which these measurements are averaged is important. Typically, 20, 30 or 60 minute averaging periods are common (Shuttleworth, 1987). This is based on the scales of atmospheric motion illustrated in

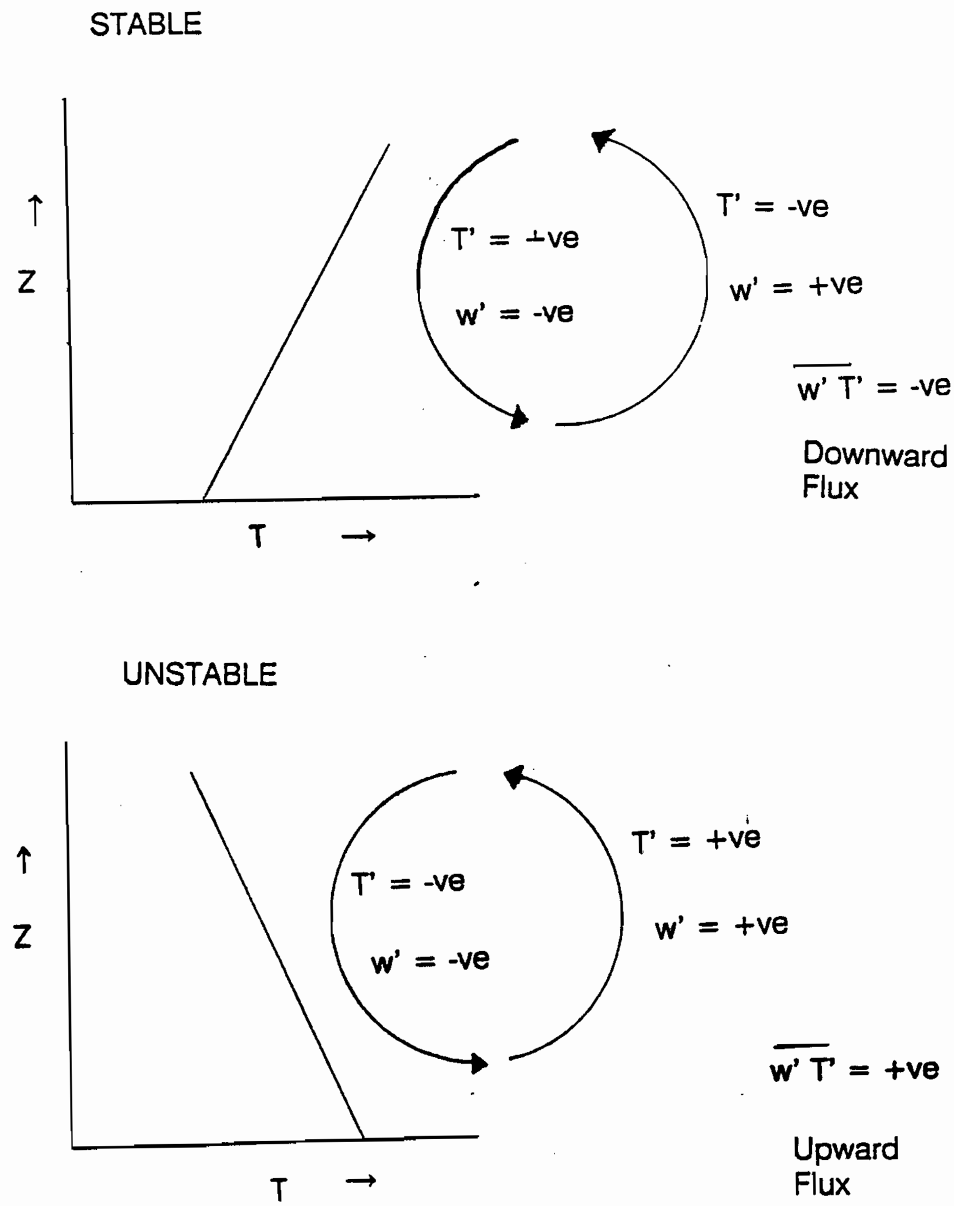


Figure 1: Illustration of changes in the average of the instantaneous fluxes with changes in stability

Figure 2. Essentially two scales of motion exist in the atmosphere, synoptic and turbulent (Stull, 1988), between which exists a 'spectral gap' in which very little motion occurs. By averaging over periods on the order of the spectral gap one is most likely to include all turbulent scale motion and avoid the influence of synoptic scale motions.

Although eddy correlation is advantageous in that it produces more accurate and reliable results, there are disadvantages in its implementation, particularly with respect to costs. Standard eddy correlation instruments are expensive and fragile. Use of the propeller anemometer in conjunction with fine wire thermocouples (the instrumentation chosen for this particular study) is less costly and more robust, although slightly less accurate. Thus, in implementing a study using the eddy correlation approach, one must weigh the advantages and disadvantages in conjunction with the type of study being conducted (ie. short term versus long term; instruments which are easily accessible versus those at a remote site).

2.3 Turbulent Flux Measurements

Turbulent fluxes have been the focus of several recent large scale projects. The NASA GTE ABLE-3a experiment was conducted over tundra in Alaska to measure trace gas concentrations. As the transports of these gases is expected to be similar to those of heat and moisture, the turbulent fluxes were of major interest in this study (Fitzjarrald and Moore, 1990). The FIFE (First Islscip Field Experiment) was conducted over a grassland in Kansas to better understand surface energy forcings and to relate these to remotely

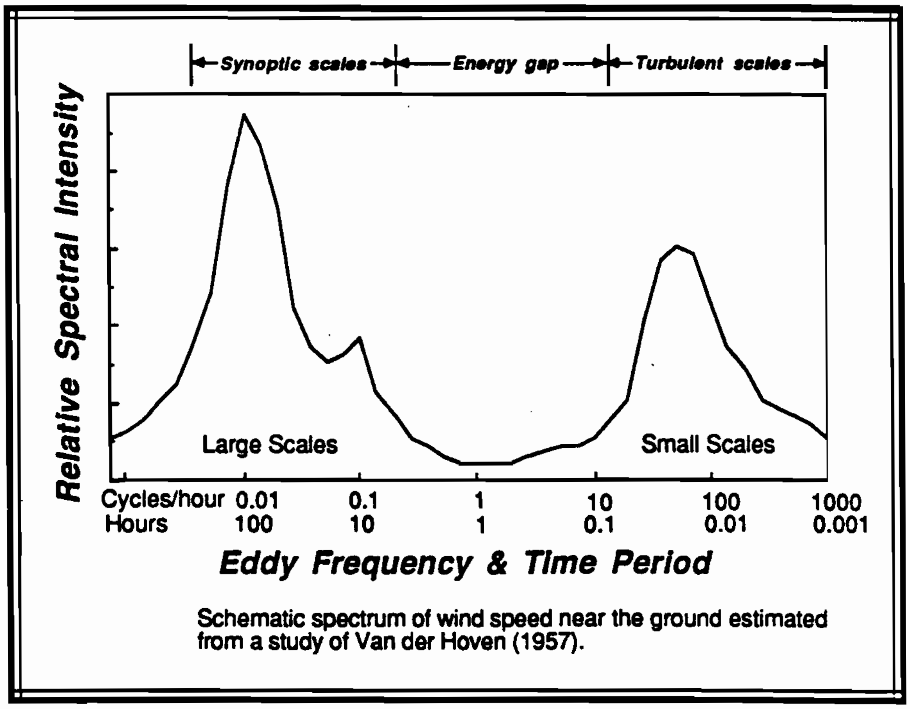


Figure 2: Scales of atmospheric motion (Stull, 1988)

sensed data (Sellers et al., 1990). A major influence in this work has been the realization that a major problem with climate modelling is inadequate parameterizations of surface processes and thus poor initializations of models (particularly GCMs).

Flux measurements are typically performed over homogeneous surfaces with extensive fetches, however some attempts have been made to examine these fluxes over less than 'ideal' sites (McMillen, 1988; Schmid et al., 1991). For example, Schmid et al. (1991) have shown that over urban surfaces even small scale inhomogeneities can create significant differences in the turbulent fluxes.

Eddy correlation flux measurements are also used as a standard for instrumentation tests. Horst (1973) and Amiro and Wuschke (1987) used a sonic anemometer run in conjunction with the Gill propeller/temperature sensor in order to determine to what extent the propeller system underestimates heat fluxes under various conditions of stability. Erisman and Duyzer (1991) used an eddy correlation system and a gradient technique to compare estimates of surface exchanges using 20 minute averaging periods and found good agreements between the results of the two systems. Furthermore, recent work has suggested that there is potential for estimating sensible heat fluxes from the standard deviation of temperature fluctuations and the mean wind speed, and has provided reasonable results compared to estimates using an eddy correlation system (Weaver, 1990; Lloyd et al, 1991).

2.4 Turbulent Fluxes over Ice and Water

In comparison to terrestrial surfaces, relatively few turbulent flux studies have been carried out during the transition from water to ice surfaces. The most extensive work has been performed in the polar regions over sea ice.

When ice cover formation takes place, large changes occur in the turbulent heat flux exchange between the surface and the atmosphere. With an ice cover, there is a decrease in evaporation and a decrease in absorption of solar radiation by the surface (Maykut, 1986). Arctic ice modelling work performed by Maykut (1978) indicates that thin ice is very important with respect to heat input into the atmosphere. In the central Arctic, Maykut (1978) estimates less than 1% of the area is young ice less than 1 meter thick (an area which may contribute up to 30% of the Arctic fluxes). Thus the contributions by heat fluxes in the Arctic to the total energy balance of the area is potentially quite large (something not considered in large scale models which assume homogeneous thick ice over the entire area).

Thorpe et al. (1973) claim to have published the first eddy correlation Arctic flux measurements. The measurement period was in April during which the air temperature was never greater than 0°C, and they obtained an average sensible heat flux value of 4.18 W m^{-2}, over slushy wet 2 meter ice.

The Aidjex Lead Experiment (ALEX) was an extensive study performed to examine the heat flux from Arctic leads in winter. Evidence suggests that leads are potentially a major sensible and latent heat flux source during the winter. Fluxes over

Arctic leads have been estimated using two towers and an integration technique (Andreas et al., 1979; Andreas, 1980; Andreas et al., 1982), and the seasonal flux exchanges in Antarctica have been studied using the profile method (Allison et al., 1982; Allison and Akerman, 1980; Allison, 1973). Studies in these two regions indicate extensive differences in terms of the relative importances of sensible and latent heat fluxes. Whereas in the Antarctic turbulent fluxes are approximately equal in magnitude, in the Arctic, sensible heat fluxes are two to five times greater than latent heat fluxes. The major reasons for these differences are the lower relative humidities, and the greater wind speeds (which inhibit surface melting) in the Antarctic (Maykut, 1986). Allison et al. (1982) recorded in Mawson Antarctica, turbulent fluxes of several 100 W m^{-2} one month prior to freeze-up, turbulent fluxes of 40 W m^{-2} with ice less than 0.2 m thick, and even smaller fluxes with thicker ice. The fluxes measured prior to ice cover formation had a large daily variation, and it was suggested that the fluxes just prior to the freeze-up would have been even greater than those measured one month before. Average wind speeds in Mawson exceed 10 m s^{-1} (Allison et al., 1982).

Wettlaufer et al. (1990) examined the oceanic heat flux (water/ice interface flux) by taking temperature and ice thickness measurements and obtained a 0 to 37 W m^{-2} range of values. They pointed out significant temporal and spatial variations of the oceanic heat flux. This suggests large spatial variations in the surface/air sensible heat flux (although some horizontal smoothing may occur).

Said and Druilhet (1991) investigated boundary layer fluxes over the ocean as a means of calibration for remotely sensed data. However, they used aircraft measurements which only allowed a minimum measurement height of 50 meters (which at times may not be within the surface layer).

Rouse et al. (1989) conducted an energy balance study of the intertidal zone in Hudson Bay covering the period from a complete ice cover to open water (May to September). They examined both onshore and offshore winds. During the onshore wind periods when a complete ice cover was present, sensible heat fluxes were very small and negative (-0.42 to -0.79 MJ m^{-2} (10 days)$^{-1}$) which with the removal of the ice cover were larger in magnitude and positive (4.4 to 19.5 MJ m^{-2} (10 days)$^{-1}$). The offshore winds produced negative sensible heat flux values throughout the entire measurement period (although again, larger in magnitude with the removal of the ice cover). Obviously, the removal of the ice cover significantly increased the turbulent fluxes.

Sadhuram et al. (1988) determined the energy budget of a reservoir in India using the aerodynamic approach and found a large proportion of the fluxes were latent (96 W m^{-2} for Q_e versus -11 W m^{-2} for Q_h). However, this is largely a function of the air temperature which was generally greater than 30°C throughout the measurement period.

Bello and Smith (1990) investigated fluxes during the summertime on a tundra lake (570 m x 210 m, maximum depth 1.3 m, and a mean summer temperature of 6 to 11°C) near Churchill Manitoba and found a net downwards sensible heat flux. These values were generally large and negative during the day, small and negative at night, and only positive on rainy days.

In summary, it appears clear that the magnitude of the sensible heat flux is reduced considerably with the formation of an ice cover, and that the daily variation in fluxes decreases as well.

2.5 Water Body Characteristics

2.5.1 Water Body Classification

The type of water body under investigation has important implications for ice formation processes, as factors affecting thermal conditions within a given water body vary according to the physical characteristics (eg. depth) and flow regime of the water body.

Rivers and lakes differ in that water movement or effluence tends to be much greater in rivers, whereas in lakes water tends to be relatively stagnant. Much of the literature dealing with temperate lakes is based on the assumption that they are dimictic, or have two annual circulation periods, the spring and the fall (Ashton, 1986). On the other hand, literature dealing with rivers generally assumes high water velocities and turbulent conditions. This tends to present a problem when dealing with conditions which fall between the two.

Relatively little work has been done solely relating to reservoirs. Gosink (1987) attempted to model water temperatures in northern lakes and reservoirs, and Rossinskii (1979) provided a very comprehensive and thorough review of the thermal regime of reservoirs based on studies in the USSR. In his review, Rossinskii (1979) suggested that reservoirs were essentially 'backwater in rivers' which had regimes similar to those of lakes, but differed in that they tended to have more effluence and often elongated shapes. He classified reservoirs into two categories: shallow and deep. Basically, shallow reservoirs are up to 20-25 m in depth and have a large annual temperature variation of the bottom water. Deep reservoirs, on the other hand, are greater than 40 m deep and the bottom water temperature variation is small. Anything between (ie 25-40 m deep) can be classified as either depending on water movement and size. On this basis, Lac St. Louis may be defined as a shallow reservoir.

2.5.2 Pre-Ice Cover Conditions

Generally, with the onset of cooling in fall, the degree and speed with which a water body will cool is mainly a function of meteorological conditions. However, it is also affected to some degree by the currents, turbulence, and the lake bottom morphology (Bengtsson, 1981). Typically in lakes and reservoirs there exists two types of thermal conditions. If the water body is relatively shallow and/or there is sufficient mixing, the temperature gradients should be relatively uniform throughout the depth and the water temperature should follow the air temperature quite closely throughout the summer. Under such conditions, no thermocline develops, and the heat exchange with bottom sediments becomes important. Thus Rossinskii (1979) suggests that the primary thermal process is the heat exchange between the water and atmosphere, while a reactive factor is the heat exchange between the water and the bottom sediments (which is a function of the water-atmosphere heat exchange).

Conversely, in deep and relatively stagnant water bodies (typically deep reservoirs or lakes with little or no throughflow), a thermocline often develops (ie strong surface heating in the summer) and hence a nonuniform water temperature profile in which only the upper water layer follows the air temperature variation to any degree.

Michel (1971) has shown that in fall, at the beginning of the winter, the evaporative heat loss by the water body is approximately equal to heat gain by solar radiation. Therefore, the air-water interface heat transfer can be estimated by the difference between the air temperatures and water temperature, and a surface heat transfer coefficient. Bengtsson (1981) suggests a similar equation for the rate of heat loss.

Rossinskii (1979) shows that in shallow reservoirs, the water temperature decrease closely follows that of the air temperature , and that the water temperature through the entire water column is close to 0°C just prior to ice cover formation. Before freezing, all other things being equal, the water temperature of a shallow water body will be lower than that of a deeper water body. This is clearly established as only the upper layers of a deep water body need cool close to 0°C in order to promote ice cover formation.

Initial ice cover formation occurs only along shores (Bengtsson, 1981; Michel, 1971). Water near the shores comes into contact with the colder material that is more conductive, and the ice formation spreads towards the centre of the water body (Michel, 1971).

2.5.3 Water Body Heat Exchanges

2.5.3.1 Wind

An important factor operating on an ice free water body is the wind. Bengtsson (1978) studied circulation induced by wind in lakes and suggested that it was very important as a mechanism for generating flow. The wind results in shear stress which produces turbulent mixing and surface currents (Ashton, 1986), and this tends to reduce stratification within the water body.

Wind also plays an extremely important role in ice formation and breakup periods, as a strong wind can inhibit ice cover formation and contribute to breakup. In addition, as the effect of the wind increases as fetch increases, larger lakes will be more strongly affected by wind than smaller lakes (Ashton, 1986). Rossinskii (1979) notes that although winds make ice cover formation difficult, they cool the water body more quickly. For a deep water body, as there exists a temperature stratification, strong winds just result in cooling of a deeper layer. Ice formation is therefore determined by a great number of interacting factors, and the final cooling and ice cover formation stage fluctuates to a large degree (Michel, 1971).

2.5.3.2 Bottom Sediments

Heat flow from bottom sediments is a very important factor which can influence lake thermal conditions (Adams, 1981; Ashton, 1986; O'Neill and Ashton, 1981; Rossinskii, 1979). Naturally, the importance of this energy source in the winter will change with variations in the physical conditions of the water body. One would expect, however, that the more shallow the water body is, and the more mixing that occurs, the more heat will be stored by the sediments. Ashton (1986) suggested that in addition to depth, other influences on sediment heat storage include, morphometry, latitude, and altitude.

O'Neill and Ashton (1981) examined heat transfer of bottom sediments to water bodies. They suggested that only winter sediment heat transfers were important, those in summer being negligible, and proposed a method of calculating the bottom heat flux based on the assumption of an annual water body temperature variation which closely follows the sinusoidal air temperature variation.

Rossinskii (1979) suggested that the heat flow from the bottom of the reservoir varies little over time once it has become stabilized for the winter. This is a different approach to Ashton (1986) who assumes a linear decrease in heat release by bottom sediments after about January. Rossinskii (1979) indicated that the net flow from the bottom is related to both the climate of the area, and the amplitude of variations of the bottom water temperature, and that the winter heat exchanges between the sediments and water should not vary significantly with the soil type making up the bed material. Table

1 lists monthly estimates of the heat release at 45° north latitude for a mean depth of the water body of 5 m (based on USSR data).

Table 1 : Estimates of the bottom heat flux for 45 N latitude (modified from Rossinskii, 1979)

Month	Bottom Heat Flux for 5 meter Depth (W m^{-2})
November	11.3
December	8.7
January	5.5
February	14.0

2.5.3.3 Other External Heat Sources

There are two other sources of external heat to reservoirs which, although generally negligible, should be mentioned. They include heat from the oxidation of organic materials (Bilello, 1968), and the geothermal heat flux (which according to Ashton (1986) is approximately two orders of magnitude less than the heat flux from the sediments).

2.5.4 Water Velocity

Water movement in a water body strongly influences thermal conditions within the water body essentially by promoting more mixing and less stratification. Convection is influenced mainly by gravity, wind and variations in density (Rossinskii, 1979). Even at low water velocities (0.01-0.02 m/s), Rossinskii (1979) suggests that water will circulate through the entire depth of a 20 m deep water body. The velocity also has important implications for ice cover growth. Typically, it can be assumed a water body will remain ice free if the water velocity exceeds 0.6 m/s. However, Bengtsson (1981) points out that the 'critical velocity' is also a function of the bottom roughness, depth, wind speed, and air temperature.

Stigebrandt (1978) studied the dynamics of an ice covered body of water with throughflow. The lake was divided into three regions; the inlet, outlet and lake proper. The amount of mixing which occurred between the lake and river water at both the inlet and outlet regions was strongly dependent upon the geometry of the areas, the temperature gradient in the lake, and the river water velocity. For a given area, the water velocity is the main factor in water temperature variations, as sediment heat transfers are relatively constant in a given area (Rossinskii, 1979).

2.5.5 Ice Cover

Ice will tend to be thicker in areas with less water movement. In 'effluent' water bodies, heat is released from energy dissipation due to hydraulic resistance, from the bottom, and by cooling water (Rossinskii, 1979). In a study of the heat fluxes to river ice covers, Marsh and Prowse (1987) measured water temperatures and velocity on the Liard river. Large temporal and spatial variations in the water temperature measurements were found and it was suggested that more work needed to be done with respect to spatial and temporal variations in water temperatures below ice covers. Gow and Govani (1982) examined ice growth on a water body (with maximum depth of 12 m, area of 0.46 km^2, and dimictic), and found little spatial variation at distances greater than 25m from the shore. Adams (1981) suggested that ice thickness variations may be spatially random or may show be related to prevailing wind directions. He states that black ice tends to be thinner downwind, while snow cover and white ice tend to be thicker downwind.

Numerous studies have been conducted investigating heat storage in water bodies in the winter. Bilello (1968) investigated water temperatures in a shallow lake during the winter season (the lake was 150 x 275 m, had a maximum depth of 2.2 m, with little drainage). It was found that the bottom water temperature increased to 3°C after ice had formed from 2°C prior to ice cover formation, and that with the removal of the ice cover, the temperature decreased throughout the entire depth. Marsh and Prowse (1987) on the other hand, found with the removal of the ice cover of the Liard River, the water temperature increased by 5°C within a few days. Tvede (1978) examined heat storage in a lake in Norway over a three year period, and concluded that the climate acts as a positive feedback mechanism with respect to regulating water heat loss. Thus a cold winter would produce a thicker ice cover and hence decrease heat loss, while a warm winter would produce little or no ice cover and hence increased heat loss.

2.5.6 Snow Cover

Snowcover exerts a strong influence on the heat exchanges through an ice covered water body. Snowcover decreases winter heat loss (and therefore decreases thickening) and also decreases heat gain in spring (Adams, 1981).

Rossinskii (1979) suggests that the snow and ice thicknesses are closely related and are in fact proportional; "snow and ice always strive to attain the depth at which the ability of the ice to transmit heat from the water to the atmosphere will correspond to the heat influx reaching the lower surface of the ice" (p 202).

Waite and Marsh (1978) suggest that the actual presence of a snowcover is more important than its actual depth accurately measured.

In observing the physical properties of a lake snowcover versus those of a land snowcover, Adams (1981) suggests that they differ in that the lake snowcover has: 1) a lower depth, 2) lower water equivalent, 3) poor stratigraphic development, and 4) greater spatial variability. With periodic ice sheet flooding, the snow is likely to maintain fairly low density values all winter and won't have the increases in density often found over land (as the lower layers melt or become incorporated into the ice).

2.5.7 Snow-Ice

The development of snow-ice on ice sheets is very widespread and common, and generally the result of ice cover cracks which develop and allow water from below the ice cover to 'flood' the ice cover. The formation of these cracks includes causes such as thermal stresses, water level changes, wind, uneven snow overloading, and seismic phenomena (Deriugin, 1972). Flooding of the ice cover is often initiated when the overlying snow cover exceeds the buoyancy of the ice.

Once water has flooded the ice, there are two layers of water (both at 0°C) with an ice layer sandwiched between. Consequently, no thermal gradient is developed through the ice. In this situation heat flow from the water melts the ice at the water-ice interface, while at the same time, water freezes above the ice surface and releases heat to the atmosphere through the snow. This occurs until the entire upper water layer has turned to ice (Rossinskii, 1979; Adams, 1981).

CHAPTER 3

STUDY SITE AND INSTRUMENTATION

This chapter will review in detail the site characteristics. It will provide information on both the physical characteristics of the site, the typical climatic conditions in the vicinity, and will include the criteria by which the measurements were categorized as either an over-water or over-ice source area. The instrumentation used in the study will also be described, as well as the datalogger processing, the datalogger reduction procedures, and pre-field instrument tests.

3.1 Site Location

As this research required measurements to be made over a fresh water body, and it was necessary that the instruments be monitored relatively closely and frequently, a site was chosen which was very accessible from downtown Montreal. The water body was Lac St. Louis, which is located to the southwest of the Montreal island (Figure 3). The instruments were placed on the northern shore of Lac St. Louis at Point Claire.

Instruments were located on two towers approximately 110 m apart. The first, a 4 m tower, was located on a breakwater about 25 meters offshore, while the other, a 17 m tower, was located just onshore (Figure 4). The majority of the sensible heat flux data

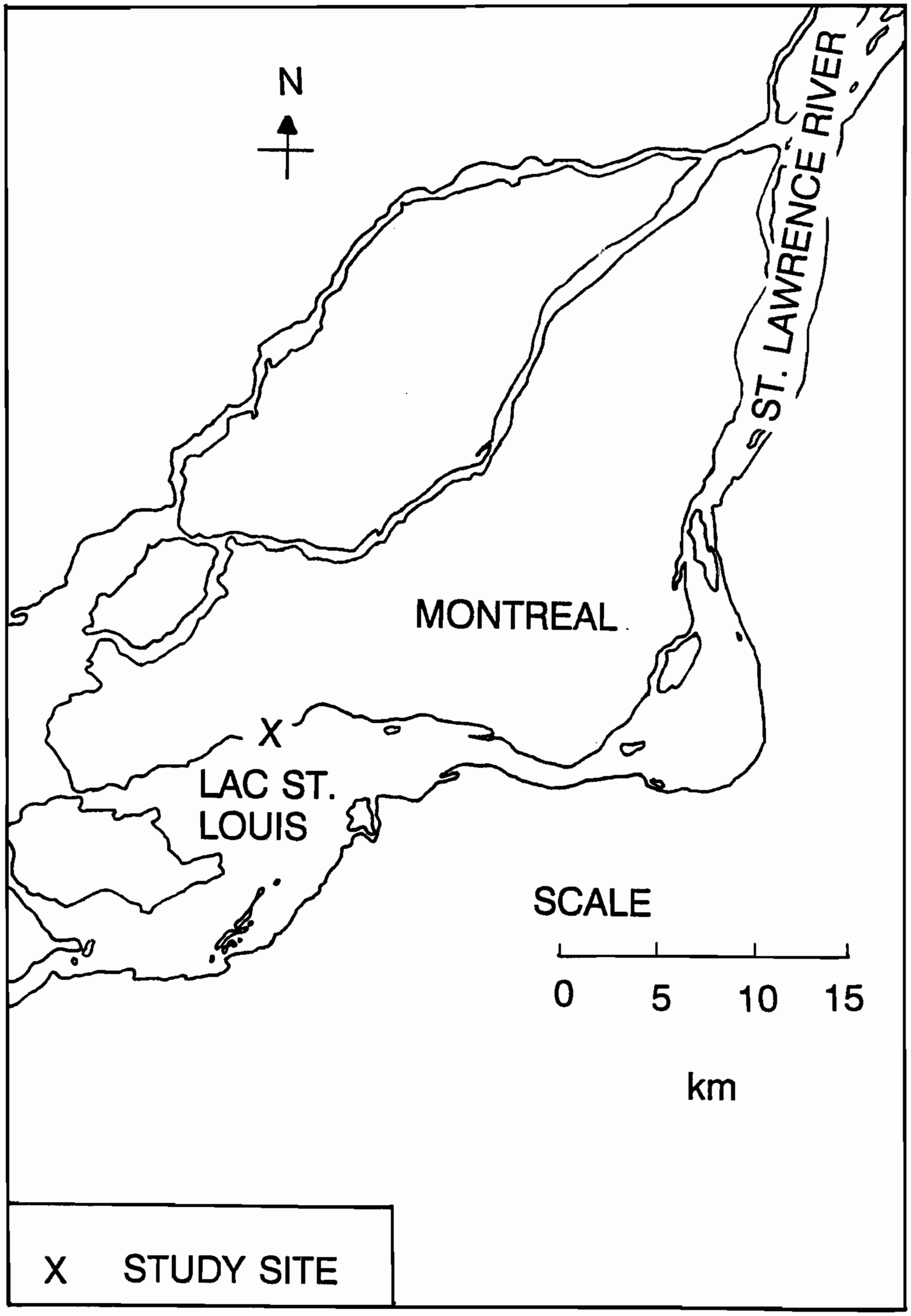


Figure 3: Study site location on the shore of Lac St. Louis, Quebec

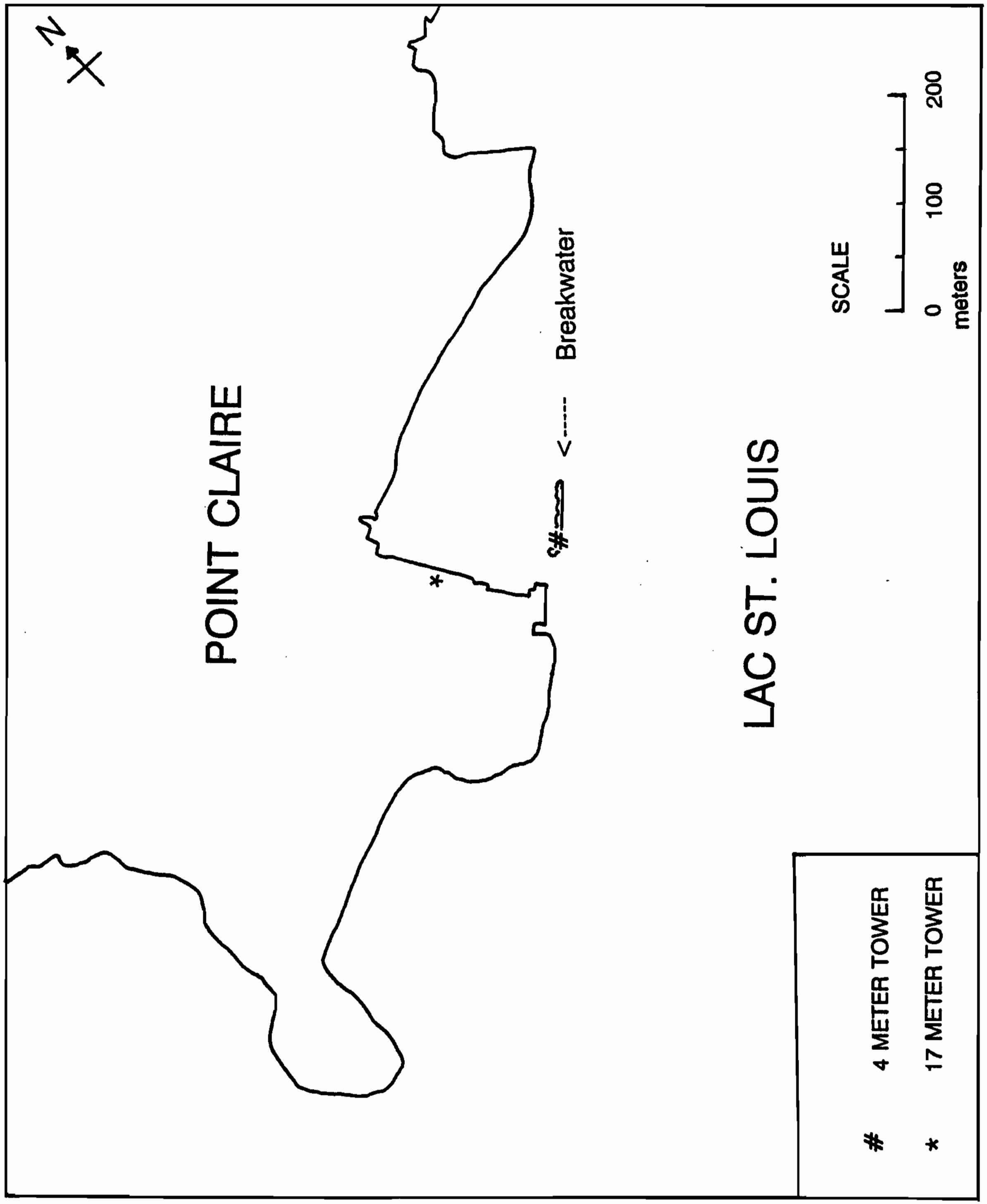


Figure 4: Tower locations on the shore of Lac St. Louis

came from the 4 m tower before 6 December 1991 and from the 17 m tower after this date.

Lac St Louis is created by an expansion of the St. Lawrence River. It is approximately 12 by 10 km in size, and for the most part is relatively shallow. Figure 5 is a bathymetric map of Lac St. Louis, produced from a navigational map. The main river channel is relatively deep (10 m) and runs close to the south shore of Lac St. Louis while the main lake basin, located to the north of the channel, is characterized by depths of .3 to .6 m. Figure 6 (LeClerc et al., 1987) shows that very strong currents exist along the southern shore of the lake in the channel indicated on the bathymetric map. Water velocities within approximately 3 km of the study area are all below 0.3 cm s^{-1}. Thus, as the instruments were located on the north shore of the lake, the effects from the channel were minimised.

Lac St. Louis, based on the discussion of water bodies in the previous chapter may be designated a 'shallow reservoir'. The mean depth as estimated from Figure 5 lies somewhere between 2-4 m. In addition, it is unlikely that the lake is thermally stratified due to the fact it is relatively shallow and has a somewhat significant throughflow.

It appears that heat exchange with the bottom sediments may be a factor with respect to heating the water (with the presence of an ice cover), as tends to be the case in 'shallow reservoirs'. It is likely that wind does not play a major role, as the lake does not have a large surface area, but that it probably exerts a strong influence for short periods of time during the ice cover breakup and decay, and may also be important in terms of thinning of the winter snow cover over the ice.

Figure 5: Bathymetric map of Lac St. Louis produced using GRASS.
Units are water depth in cm (colour-coded).
Land is denoted by black.

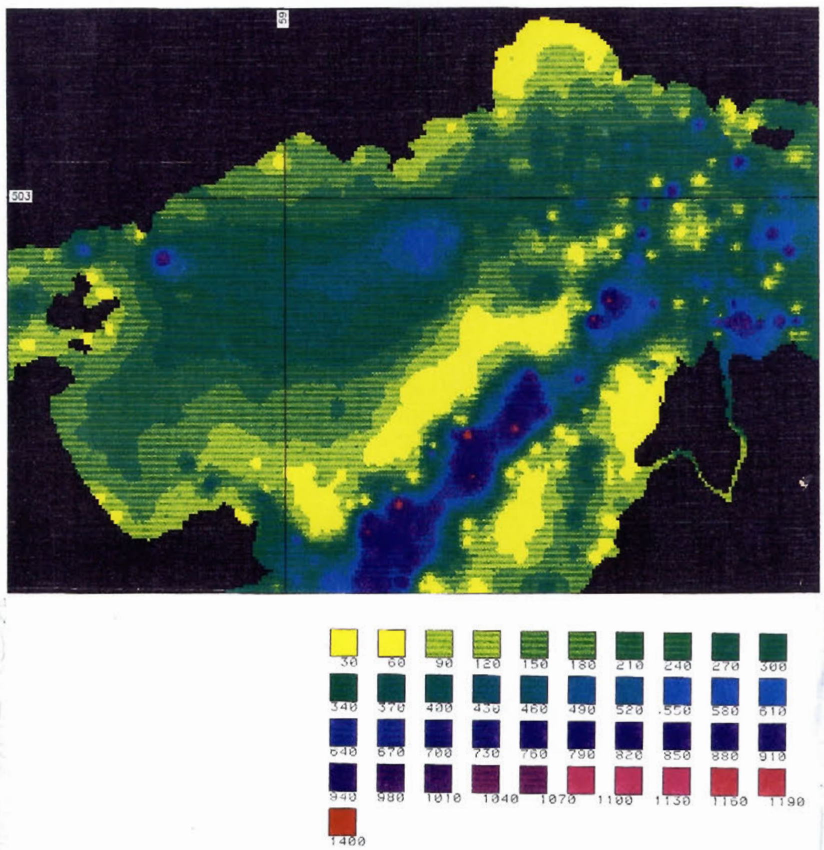
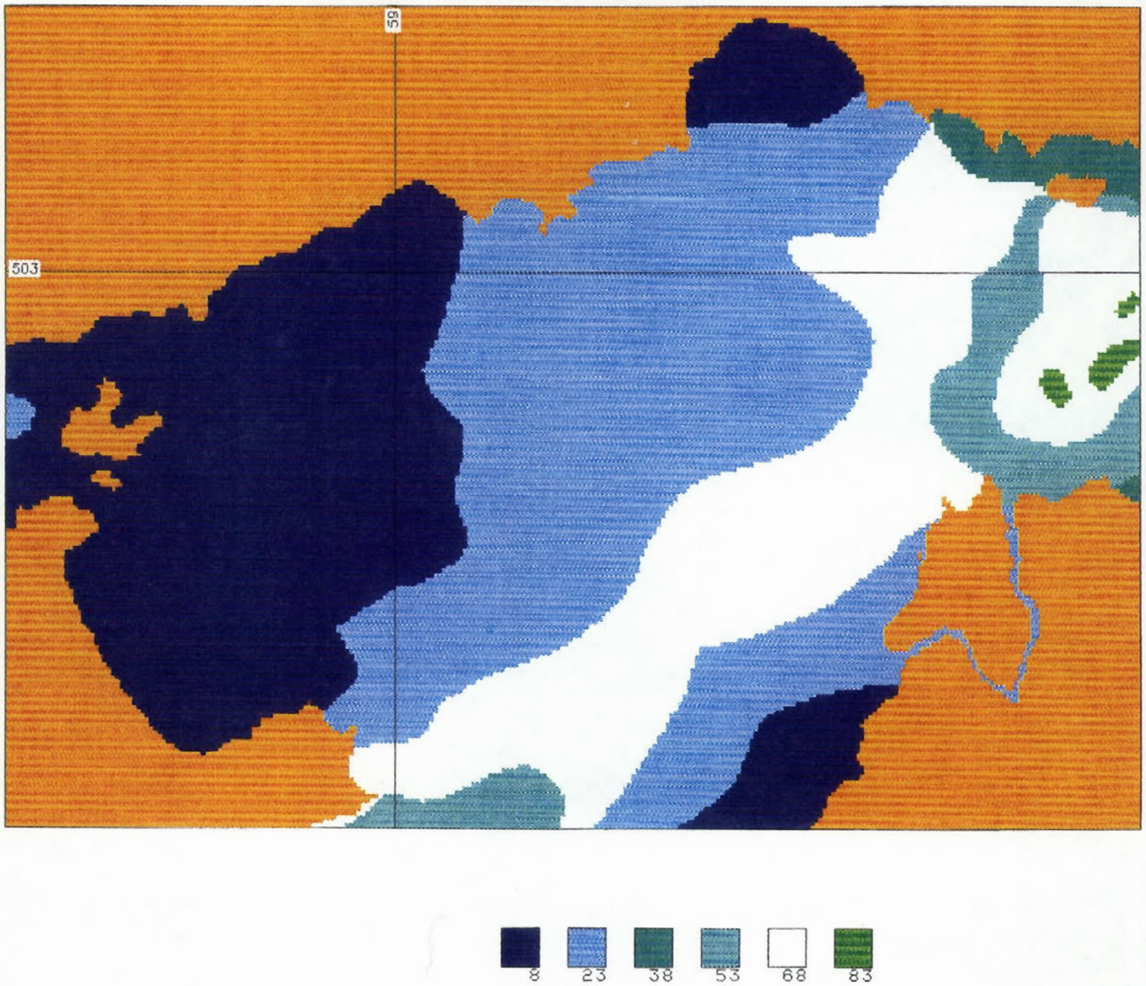

59
503
30
60
90
120
150
180
210
240
270
300
340
370
400
430
460
490
520
550
580
610
640
670
700
730
760
790
820
850
880
910
940
980
1010
1040
1070
1100
1130
1160
1190
1400

Figure 6: Map of modelled water velocities (from Leclerc et al., 1987) reproduced using GRASS.
Units are ranges of water velocity in cm s^{-1} coded with colours and numbers.
Land is denoted by orange.



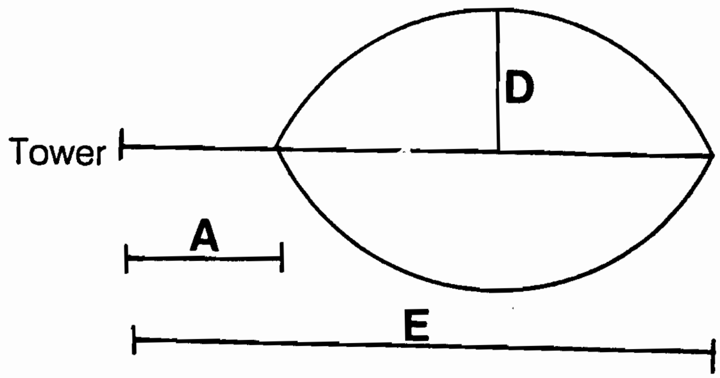
8 0.000-0.1500
23 0.1500-0.3000
38 0.3000-0.4500
53 0.4500-0.6000
68 0.6000-0.7500
83 0.7500-0.9000

3.2 Typical Conditions

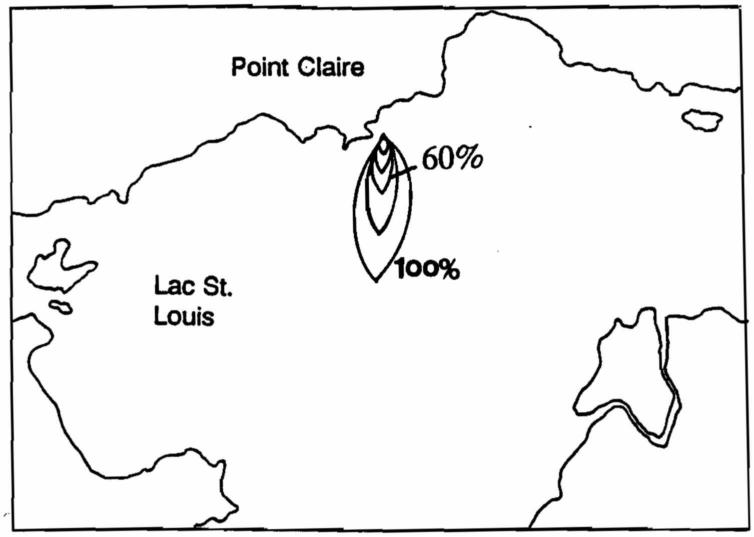
The Montreal island is approximately 30 to 40 meters above sea level (Climate of Montreal, 1987). The general climatic conditions often associated with the Montreal area are largely a function of it's geographic location. It is located along the St. Lawrence River Valley which runs in a northeasterly direction, and which is bounded to the north by the Laurentian Mountains, and to the south by the Appalachian Mountains. As a result, winds often flow parallel to the St. Lawrence River. As far as temperature and humidity are concerned, general conditions tend to be determined to a large degree by the air mass source. Typically, those air masses which originate out of the south tend to be moist and warm, those from the west and southwest tend to be mild, those from the northeast cold and moist, and those which originate from the northwest, cold and in the winter, very dry (Climate of Montreal, 1987). The conditions during 1991/92 and their representativeness are discussed in Chapter 4.

3.3 Measurement Criteria

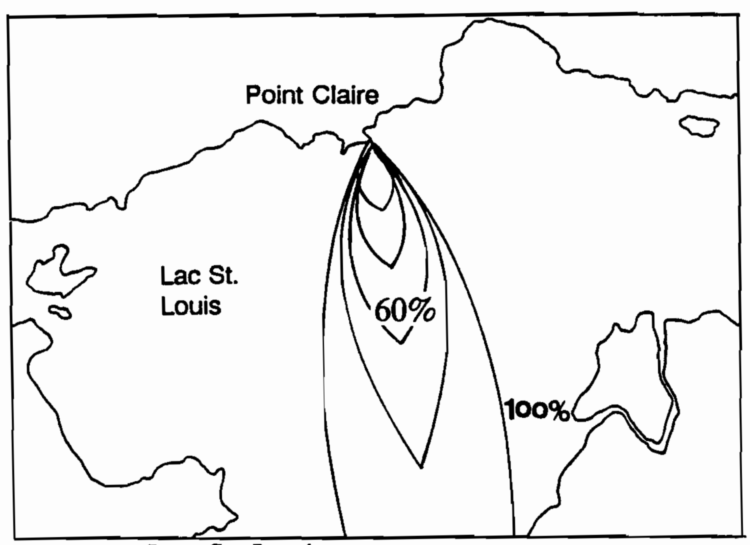
As the towers from which the measurements were made were located on or near the shore of Lac St. Louis, it is important to define the conditions or criteria under which



a) Schematic diagram of source area dimensions.



b) Source area plots for 4 m tower in 20 % intervals.



c) Source area plots for 17 m tower in 20 % intervals.

Figure 7: Source area estimates over Lac St. Louis.

must be between .5 and 6 (Schmid and Oke, 1990).

Model runs were made for unstable conditions which met the above criteria for the period 14 November to 3 December 1991. The minimum roughness length values were used (z_o = .001 m) as values over water and ice tend to be very small (Oke, 1987). The standard deviation of the lateral wind fluctuation (SV) was estimated using:

$$SV = SD*u, \tag{7}$$

where SD is the standard deviation of the wind direction (in radians), and u the average wind speed over the time interval (Schmid and Oke, 1990).

Hourly values were used as there tended to be a degree of variation in stability from hour to hour. By looking at unstable conditions, the purpose is to provide a minimum set of source areas for each tower, as the source area will always be located a greater distance from the tower under stable conditions. Tables 2 (a) and (b) lists the average distances and their standard deviations for each confidence interval (in 10% steps) for 77 runs where z=4 meters, and z=17 meters. It is important to note, however, that the SAM runs were made for data collected before 21 December, 1991, as equipment problems halted collection of atmospheric stability measurements. This time covered for the most part, the open water period. This method of obtaining the flux source area provides a rough estimate only. The estimated areas are quite wide, and as a result some of the estimated source areas overlap onto adjacent land. However, it does provide a rough idea of the extent across the lake to which the fluxes may originate. Figure 7 (b) and (c) are plots of the source area estimates for both towers from the information listed in tables 2 (a) and (b). Based on the SAM estimates, the flux source area generally appears to extend a maximum distance of about 1-2 km away from the 4 m tower, and up to 3-7 km away from the 17 m tower under unstable conditions. Although the distance may extend quite a distance away, the majority of the flux contribution is from areas closer to the towers.

As noted previously, under stable conditions, the source areas will extend greater distances from the tower than under unstable conditions, so the plots indicate minimum source areas for the given confidence intervals.

3.3.2 Direction

Although there is some land contained in the source area plots, it is a small enough fraction that it is not likely to have an effect on the measurements. As a general rule, wind directions reflect over-water/ice source areas: 1) between 50 degrees and 270 degrees for the 4 meter tower, and 2), between 63 degrees and 270 degrees for the 17 meter tower.

Table 2 a): The average and standard deviation for the 4.0 meter tower of the SAM estimates (using 77 runs). The dimensions A, E and D are shown in Figure 7.

%	A	(m)	E	(m)	D	(m)
	AVG	STD	AVG	STD	AVG	STD
10	33.4	2.18	201.7	41.7	62.5	14.2
20	28.1	1.5	285.5	70.3	77.5	17.7
30	24.9	1.2	379.7	100.2	94.5	21.9
40	22.5	1.1	493.1	140.6	114.8	27.2
50	20.6	1.0	629.2	188.3	138.8	33.6
60	19.1	0.9	795.6	248.3	167.9	41.7
70	17.8	0.9	999.9	320.4	203.2	51.6
80	16.6	0.9	1255.5	407.9	247.1	63.8
90	15.5	0.9	1578.5	506.1	302.7	78.6
100	14.6	1.0	1998.0	612.8	375.1	96.5

Table 2 b): The average and standard deviation for the 17 meter tower for the SAM estimates (using 77 runs). The dimensions A, E and D are shown in Figure 7.

%	A (m)		E (m)		D (m)	
	AVG	STD	AVG	STD	AVG	STD
10	152.1	28.6	800.1	294.3	224.1	55.9
20	130.6	22.3	1085.8	463.7	267.6	71.2
30	116.0	19.3	1414.9	645.2	318.9	89.7
40	105.3	17.2	1796.1	878.0	377.3	112.8
50	96.7	15.6	2253.6	1157.0	447.4	141.1
60	89.4	14.5	2808.5	1501.8	531.7	175.9
70	83.0	13.6	3494.0	1916.3	635.3	217.7
80	77.2	12.9	4361.8	2419.4	766.4	268.1
90	71.8	12.3	5498.5	3008.7	938.5	328.3
100	66.6	11.9	7046.4	3674.7	1177.8	400.8

3.4 Instruments

Two towers (4 and 17 m) were erected so as to obtain sensible heat flux (Q_h) measurements. The 4 meter tower was used to obtain standard information (wind speed and direction, air temperature). Details regarding placement and location of the towers has been discussed earlier in the chapter. The following will outline the instruments used in this study and their location on the two towers.

3.4.1 Temperature

The air temperature was recorded using a Campbell Scientific 107 Temperature Probe housed in a Gill Radiation Six Plate Radiation Shield. The probe has an accuracy of +/- 0.4°C over the temperature range of -33°C to +48 °C. Temperature measurements were taken every minute and averaged over the hour. The values were processed and collected on a Campbell Scientific CR10 datalogger.

3.4.2 Direction and Speed

The wind directions and speed were collected using a Met One 013 Wind Speed Sensor, and a Met One 023 Wind Direction Sensor. The 013 Wind Speed Sensor has an accuracy of 2% and a starting threshold of 1.9 km h^{-1}. The 023 Wind Direction Sensor has an accuracy of +/- 15 degrees and a starting threshold of 2.4 km h^{-1}. Both sensors can operate in winds up to 241 km h^{-1}, and with an ice load of up to 4.8 cm. As with the temperature measurements, the wind speed and direction values were hourly averages of values collected every minute. Again, these measurements were recorded using a CS CR10 datalogger.

3.4.3 Fast Response Wind Speed

For the purpose of obtaining fast response wind speed measurements, two Young Gill uvw Anemometers (Model 27005) with Model 08274 Expanded Polystyrene 22 x 30 cm propellers were used. This system has a starting threshold of 0.3 m s^{-1}, a range of 0 to 30 m s^{-1}, and a distance constant of 1 m. The vertical arm provided a measure of the fast response vertical wind speed (w') whereas the horizontal arms provided a measure of the fast response horizontal wind speed (measurements were recorded every 0.09375 seconds). These horizontal and vertical wind speed fluctuations were immediately used in the calculation of fluxes and stability which were then averaged and recorded on an hourly basis. The information was processed and stored in a CS CR10 datalogger.

3.4.4 Fast Response Temperature

In order to obtain fast response temperature fluctuations (t'), thermocouples were constructed using unshielded, single junction 25 μm diameter chromel-constantan (type E) wire. These wires were glued to Y-shaped wood frames which allowed the thermojunction to be free of obstruction. These 25 μm chromel-constantan wires (of approximately 15 cm in length) were then attached to 20 gauge μm chromel-constantan wire which was then connected to the CS CR10 datalogger. As with the fast response wind speed measurements, the fast response temperature fluctuations were collected every 0.09375 seconds before being processed further. The final outputs were hourly averages.

3.4.5 Instrument Location

The 4 meter tower supported the bulk of the instrumentation (Figure 8), while the 17 meter tower supported a single Gill propeller anemometer (vertical axis) and two fast response thermocouples (Figure 9 (b)). The cup anemometer, windvane, temperature probe, 3-axis Gill Propeller Anemometer, and 2 fast response thermocouples were attached to the 4 m tower (Figure 9 (a)). The temperature probe, cup anemometer and windvane were attached to one CS CR10 datalogger, while a separate CS CR10 datalogger was used to store information from the 3-axis Gill Anemometer and the fast response thermocouples. Figure 10 is a close up of a fast response thermocouple. On each eddy correlation system, two fast response thermocouples were used to obtain two sensible heat flux estimates for each location. The second thermocouple provided a backup should the other cease to operate.

Figure 8: Location of 4 m tower on breakwater.

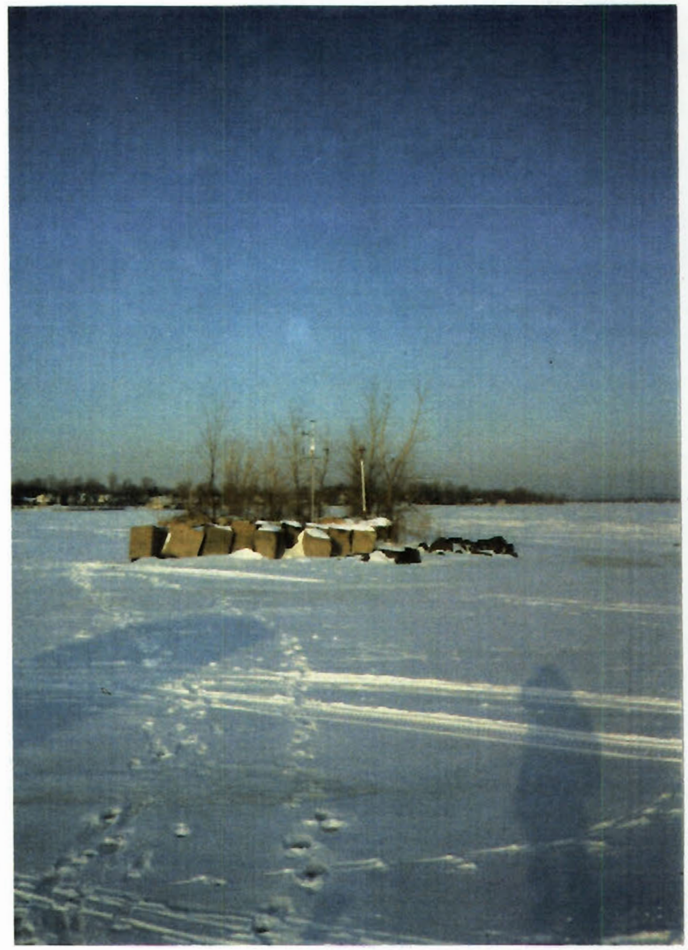
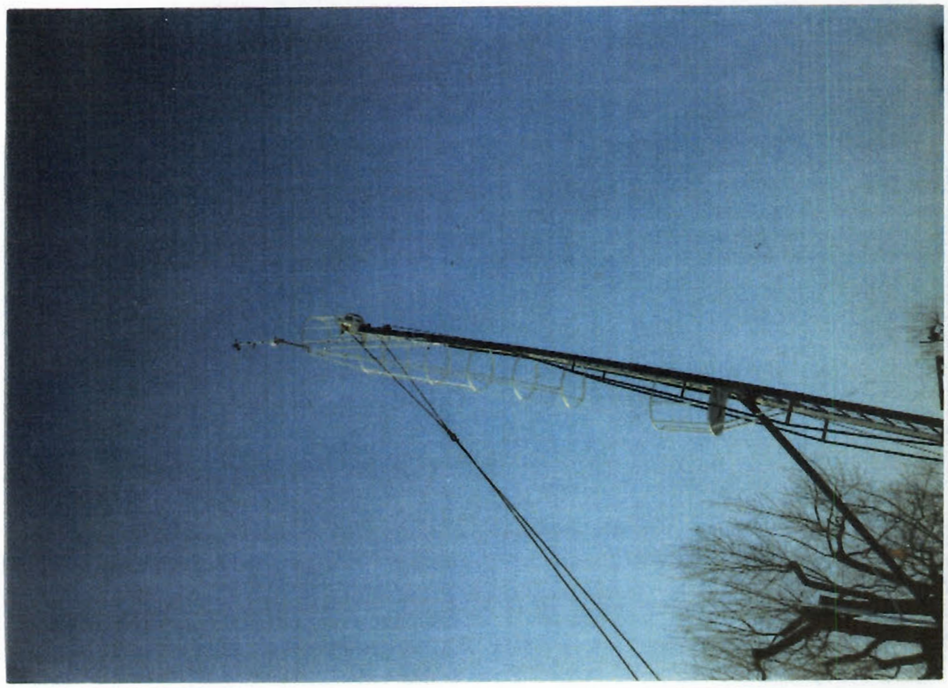


Figure 9 a): Close-up of 4 m tower instrumentation setup.

Figure 9 b): Location of Gill/thermocouple system on 17 m tower.



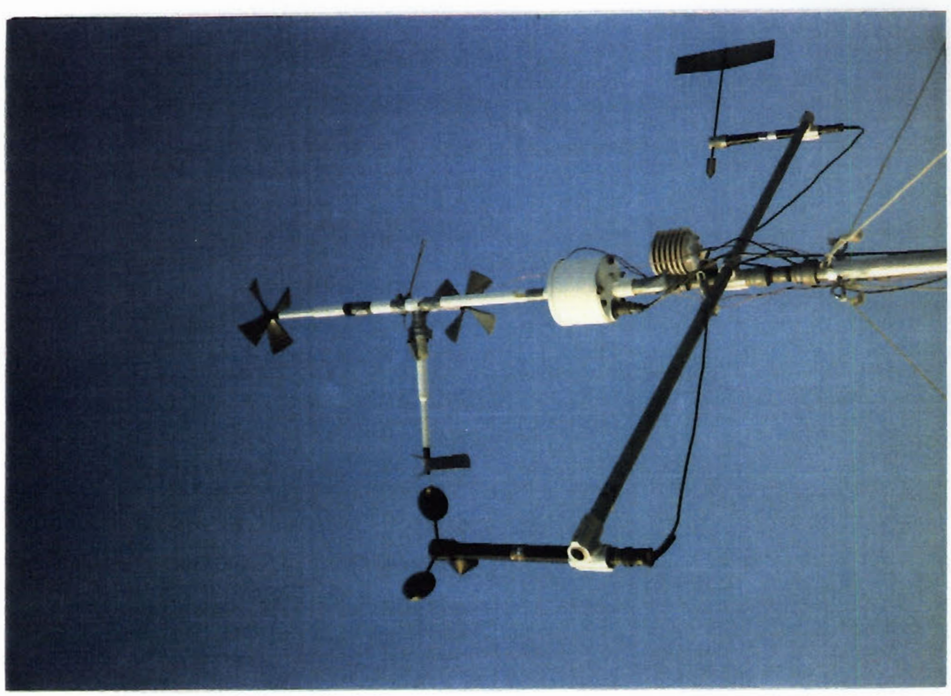
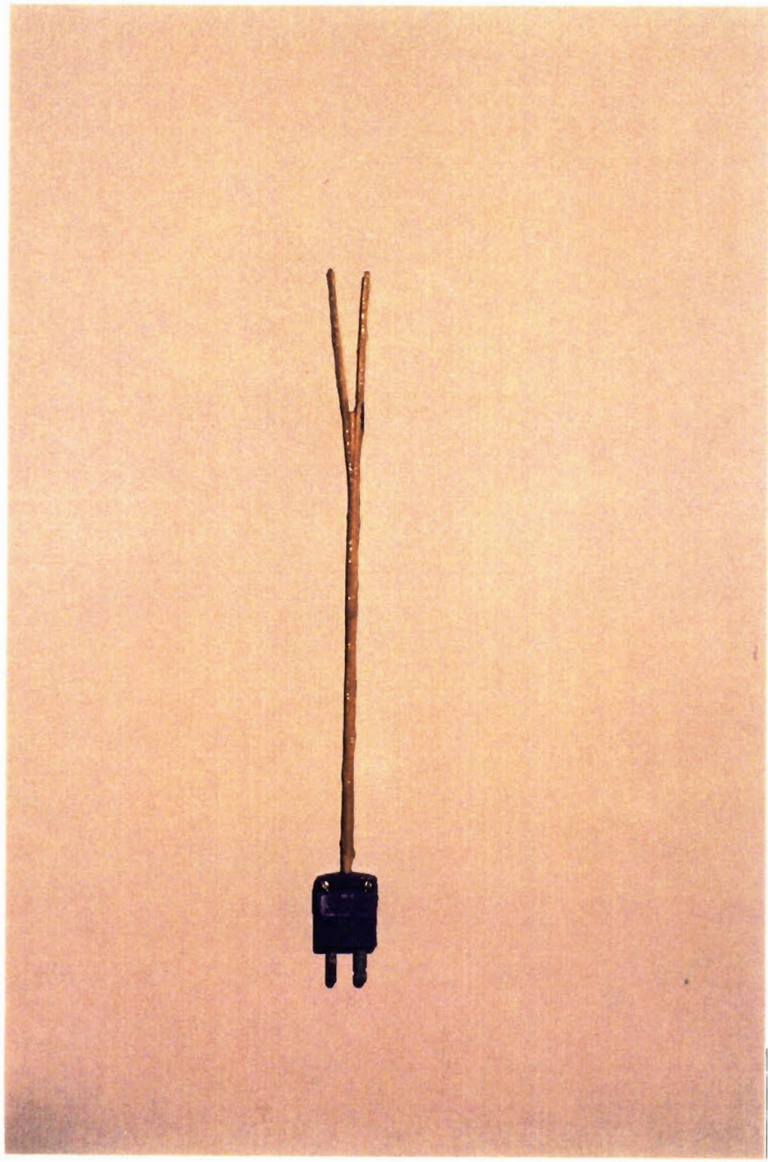


Figure 10: Close-up of a Fast Response Thermocouple.



3.5 Eddy Correlation and Stability

3.5.1 Datalogger Processing

Recording vertical and horizontal wind speeds as well as temperature fluctuations every 0.09375 seconds for extensive periods of time requires considerable storage capacity; therefore it was necessary to process much of the data instantaneously and average over the required time period (in this study one hour). Appendix 1 contains the CS CR10 datalogger programs used on the 17 and 4 meter towers. Appendix 1A contains the datalogger programs used on the 17 meter tower to output values for the Q_h calculations, and Appendix 1B contains the CS CR10 datalogger program used on the 4 meter tower to output values for the Q_h and stability calculations.

The equation for the calculation of the sensible heat flux is (Oke, 1987):

$$Q_h = \rho \, C_p \, \overline{w't'} \tag{5}$$

where ρ is the air density, C_p is the specific heat of air, and $\overline{w't'}$ the average of the product of the instantaneous vertical wind speed and temperature fluctuations. The air density and specific heat of air constants used in the program were 1.188 kg m^{-3} and 1010 J kg^{-1} K^{-1} respectively (Oke, 1987). In order to determine the fluctuating wind and temperature components the instantaneous wind speed and temperature measurements were low pass filtered and the instantaneous deviation subtracted from the running mean.

Thus the output consisted of two hourly $\overline{w't'}$ values (one calculated from each thermocouple) and the two corresponding hourly Q_h values. As air density is temperature dependent, Q_h values were subsequently corrected on the basis of the hourly air temperature.

The Monin-Obukhov Stability Length (L) was used to determine the atmospheric stability:

$$L = \frac{u^* \, \overline{T}}{g \, k \, \overline{w't'}} \tag{8}$$

where u* is the frictional velocity $((u'w')^{0.5})$, $\overline{T}$ the average air temperature, g the acceleration due to gravity (9.8 m s^{-1}), k the von Karman's constant (0.4), and $\overline{w't'}$ the average of the product of the instantaneous vertical wind speed and temperature fluctuations. Thus g and k were constants, $\overline{w't'}$ was output already on an hourly basis for the purpose of calculating the Q_h, $\overline{T}$ was recorded using the temperature probe, and it was only necessary to output $\overline{u'w'}$ in order to calculate the Monin-Obukhov stability length. The instantaneous single horizontal wind speed fluctuations were calculated based on squaring each of the horizontal fluctuations (u' and v') and taking the square root of their sum ($(u^2+v^2)^{0.5}$). Again, hourly averaged values of $\overline{u'w'}$ were stored by the datalogger.

3.5.2 Processing Datalogger Output

A set of simple programs were written to allow calculation of the sensible heat flux and atmospheric stability from the information output by the dataloggers. Appendix 2A contains the program used to calculate the Monin-Obukhov Stability Lengths (L) and the actual stability values (z/L), while Appendix 2B contains a program which uses the output from the previous program to calculate new hourly sensible heat flux values from $\overline{w't'}$ depending upon the average air temperature (T). Table 3 (at the end of this chapter) lists the air density values (as a function of temperature) which were used in the correction of the sensible heat values. Another important component of the data processing was the correction of the fluxes for stability. These corrections are discussed below (section 3.5.4).

3.5.3 Gill u v w Eddy Correlation System

Many small scale studies of evapotranspiration have used a Gill propeller anemometer in conjunction with a temperature sensor to determine the sensible heat flux within an energy balance approach (Milne et al., 1985; Spittlehouse and Black, 1979; Amiro and Wuschke, 1987; Amiro et al., 1988).

Studies conducted by both Shuttleworth and Black (1979) and Milne et al. (1985) used 20 minute averaging periods and a microbead thermistor as the temperature sensor in an eddy correlation system to measure forest transpiration. Milne et al. (1985) reported the system as having potential, while Spittlehouse and Black (1979) found problems relating to instrument sensitivity as a result of low wind speeds at the measurement height (4.5 meters above the canopy). Similar problems with stalling of the propeller due to low wind speed (and hence underestimates in the sensible heat flux) were encountered by Amiro and Wuschke (1987) again in an evapotranspiration study over a forest drainage basin. However, they found the instrumentation system useful in that its maintenance over a long period of time (5 months) was relatively easy. Amiro et al. (1988) used the same instruments in another evapotranspiration experiment, and, like Amiro and Wuschke (1987), they multiplied the sensible heat values by a factor of 1.15 in order to correct for the poor frequency response of the propeller anemometer. Amiro and Davis (1988) used this eddy correlation system to examine the statistics of atmospheric turbulence in a black spruce forest canopy.

3.5.4 Eddy Correlation Errors

It is important to be aware of the errors associated with the instrumentation used to obtain sensible heat flux values. The errors discussed are mainly related to the wind speed sensor, in this case the Gill propeller anemometer.

Hicks (1972) estimated that an 8% loss of fluxes occurred using a propeller anemometer at a 5 meter height, an error which decreased with the height of the tower. Sources of error are outlined by numerous other authors (Milne et al, 1985; Spittlehouse and Black, 1979; McBean, 1972) which may account for under-measurement of heat fluxes. Milne et al. (1985) pointed out that the tilt of the propeller anemometer with respect to the measurement surface may create measurement errors. Thus if the surface is not flat, the slope of the ground could result in some error. Assuming that the Gill anemometers were correctly aligned, the uniform flat character of the source area in this study would likely result in negligible error. Spittlehouse and Black (1979) suggest that error is created when average horizontal wind speeds fall below 2 m s^{-1}. With the exception of February 1992, the average wind speeds in the water source area directions were always much greater than the minimum (Chapter 4, Tables 4 (a) through (d)). This would suggest that errors in the sensible heat fluxes as a result of low wind speeds are minimal in this study. It is also pointed out that sensible heat fluxes can be underestimated as a result of the inadequate response to high frequencies of the Gill anemometer (Spittlehouse and Black, 1979). In a study of the spectra and cospectra of turbulence made over water by Miyake et al. (1970), low frequencies appear to be fairly important over this medium. This might suggest that heat flux loss as a result of inadequate instrument response may be less significant than over other media. However, no attempts were made by the author to compare these results to those obtained over other surfaces.

The 'cosine response' or 'angle of attack' (McBean, 1972) can create large errors when using the Gill Anemometer. The angle of attack is defined as "the angle between the instantaneous total wind vector and the horizontal plane" (McBean, 1972, p. 1079), and it is suggested that this error varies with conditions of atmospheric stability. Essentially cosine response relates to how the propeller anemometer responds to winds which are not parallel to the propeller shaft and it results in the introduction of an error which varies with the wind angle. This error will account for some loss in flux values. A plot of the ideal versus the measured response of the model of instrument used is supplied by the Gill manufacturer (Figure 11). The maximum cosine error occurs when winds are not perpendicular to the propeller shaft and are on the order of 12% (ie. an underestimation of 12% with winds at a 60 degree angle).

Additional errors associated with the Gill include a +/- 1% error associated with the correction from rev cm^{-1} to m s^{-1}, and, although it is not reported, it appears that there may be error associated with the calibration coefficient. This calibration is based on only two propeller RPM's, 3600 and 3000 (which corresponds to 17.6 and 14.7 m s^{-1} respectively), through which a straight line is fit. No calibration was done for lower wind speeds, wind speeds which are much more common in near ground climatological measurements.

Two studies have incorporated a test of the Gill/temperature sensor heat flux measurement versus that output by a sonic anemometer in order to obtain an estimate of the underestimation by the Gill system of the sensible heat flux. Amiro and Wuschke (1987) tested the system under unstable, neutral and stable conditions and found that a correction factor of 1.15 applied under unstable and neutral conditions, and a correction factor of 1.54 applied under stable conditions (the tests for stable conditions were performed over a snow covered surface). The values obtained by Amiro and Wuschke (1987) were similar to those suggested by Horst (1973) of 1.15 and 1.58 for neutral and stable conditions respectively. The sensible heat fluxes in this study were multiplied by

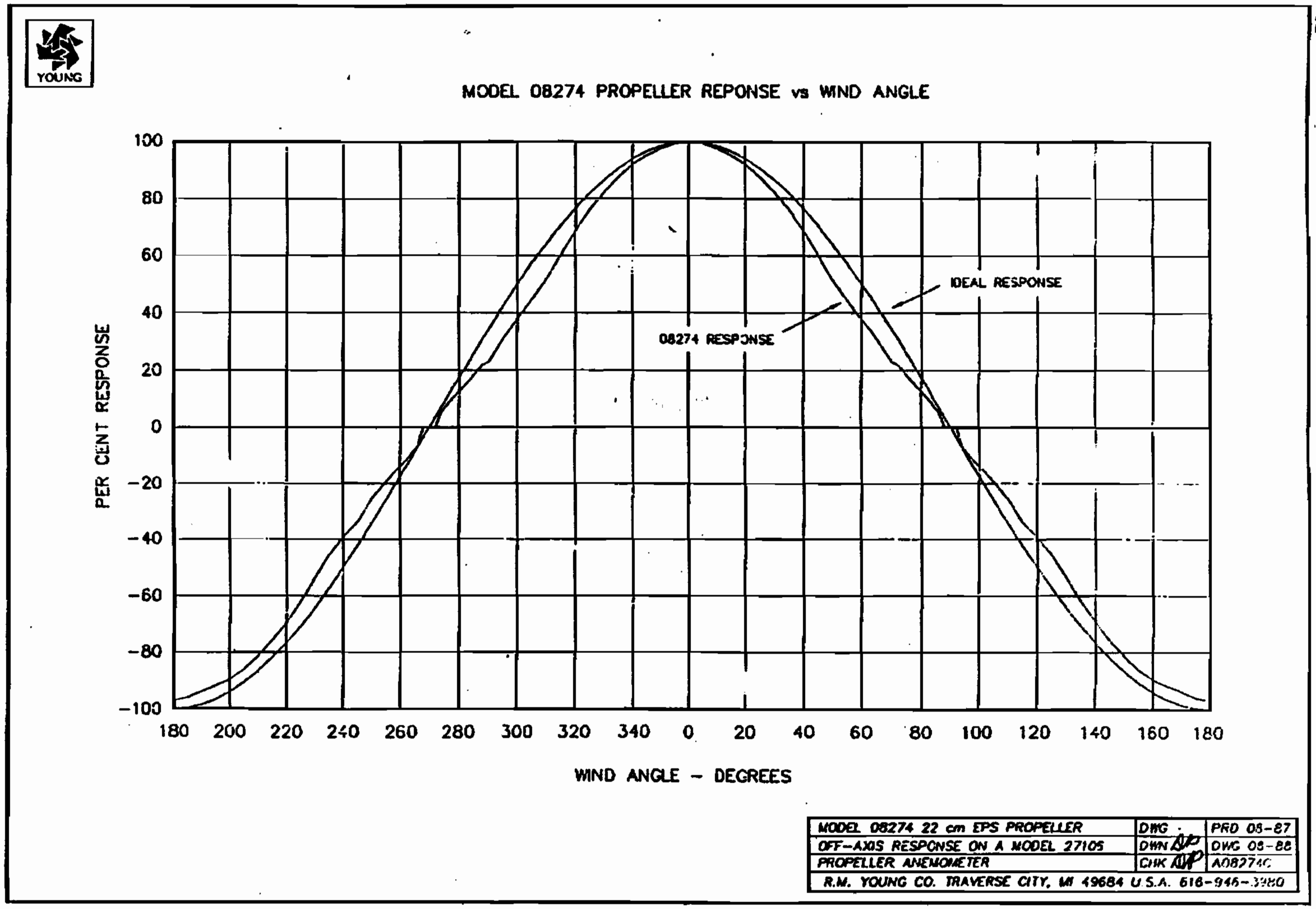


Figure 11: Ideal versus measured response of Gill supplied by the manufacturer.

1.54 for stable conditions, and by 1.15 for all other conditions, including those periods in which the stability was unknown. As a result, after 3 December 1991, all sensible heat fluxes were corrected using the multiplication factor of 1.15, creating an underestimation (of 25%) under stable conditions throughout the remainder of the period.

Use of the 25 µm wire is considered adequate. Fritschen and Gay (1979) suggest that chromel-constantan (type E) thermocouple wire is advantageous for a number of reasons including: 1) a resistance to corrosion, 2) a relatively low thermal conductivity, and 3), good homogeneity. The range of use of this wire is between -250 and 871°C. For temperature measurements greater than 0°C the error is +/- 0.5%, whereas below 0°C it is +/- 1.0% However, these are errors associated with absolute measurements which was not the purpose for which this thermocouple was used. As the thermocouples were used in this study to record only the temperature fluctuations, it is the rate of response of this thermocouple that is of importance. This 'response time' or 'time constant' is reported by the manufacturer as 0.003 s. This is the time required to reach 63.2% of an instantaneous temperature change. As the sampling interval was much greater than this (approximately 0.1 s), it is expected that the error associated with the thermocouples would be virtually negligible compared to the Gill. Amiro and Wuschke (1987) made comparisons of heat fluxes calculated using both 25 µm and 12 µm wires, and found virtually no difference in the measurements (R^2 = 0.993 for 1375 hours of data).

3.5.5 Pre-Field Tests

Prior to installing the instruments at Point Claire, the two Gills and a number of Fast Response Thermocouples were set up side by side and run using a CR10 datalogger and a 21X datalogger. The setup was the same as that used throughout the field season, however the calibration constant for the Gills was slightly different from those specified for that model. As the interest lay in the comparison of the results from the two different Gills rather than the absolute values, this difference was not considered significant. It is important to note that these test runs were conducted over agricultural fields (MacDonald College, St. Anne de Bellevue) in mid October, 1991.

The purpose of this field trial was twofold. First, it was done to compare the output using two different thermocouples with a single Gill. Secondly, it was done to determine whether the CR10 datalogger output values were similar to those of the 21X datalogger. This was important as the standard eddy correlation setup uses 0.1 second recording intervals (this is possible with the 21X), whereas the closest one can get to 0.1 second recording intervals using the CR10 datalogger is 0.09375 second intervals.

Appendix 3 contains the outputs in graphic and tabular form from this test period. The comparison of hourly Q_h values from a single Gill and CR10 over a continuous 224 hour period results in an R^2 value of 0.98, and an average difference of 1.45 W m^{-2}. The comparison of the hourly Q_h values from the two different eddy correlation setups and the different dataloggers, resulted in an R^2 value of 0.92 and an average difference of 2.79 W m^{-2}.

Table 3: Density of air as a function of air temperature (revised from Oke, 1987).

AIR TEMPERATURE (°C)	AIR DENSITY (Kg m^{-3})
> 22.5	1.168
17.5 - 22.5	1.188
12.5 - 17.5	1.209
7.5 - 12.5	1.230
2.5 - 7.5	1.252
-2.5 - 2.5	1.275
-7.5 - -2.5	1.299
-12.5 - -7.5	1.324
-17.5 - -12.5	1.349
-22.5 - -17.5	1.376
-27.5 - -22.5	1.404
< -27.5	1.433

CHAPTER 4

CHARACTERIZATION OF WINTER AND INSTRUMENTATION EVALUATION

4.1 Winter Characterization

This chapter examines the winter of 1991/92, its representativeness in terms of important meteorological variables (air temperature, wind speed and direction, and precipitation), and the effect of meteorological factors on the ice and snow cover. In addition, it will examine how these factors influenced the performance of the instrumentation, by examining the magnitude of the sensible heat fluxes, the completeness of the data record, and the possible causes of instrument problems.

4.1.1 Temperature

Temperatures during the 1991-92 winter were extremely variable. In particular, the November to February period was marked by numerous warm periods, and melting of snow and ice was relatively frequent. The unusually mild conditions experienced over North America during this period can be attributed to some degree to the presence of El Nino, a periodic upwelling of warm water in the Pacific Ocean (Deptuch-Stapf, 1992). Figure 12 is a plot of the daily air temperatures taken at the study site from 14 November

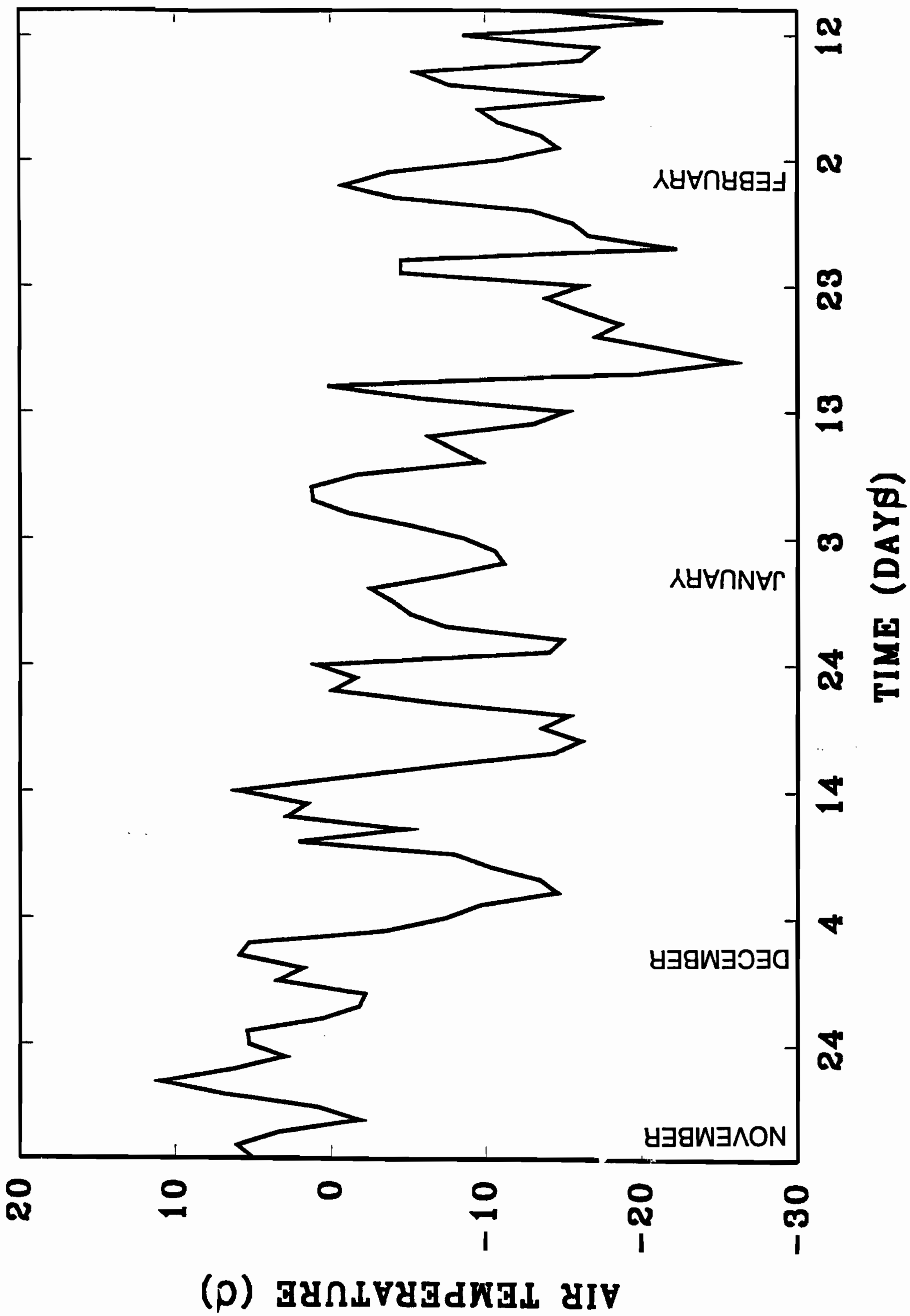


Figure 12: Daily averaged record of air temperatures at Lac. St. Louis, winter 1991/92.

1991 to 13 February 1992. These temperature measurements were taken on an hourly basis from the 4 meter tower, the hourly measurements having been averaged in order to produce the daily temperature values.

A number of comparisons were made among the measurements collected at the study site over this winter period, with either a 29 year average (1951-1980) of measurements made at Dorval (which is located approximately 5 kilometers east of Point Claire), or an 8 year average taken at MacDonald College in St. Anne de Bellevue, (located approximately 10 kilometers west of Point Claire). Comparisons of air temperature information for the months of December and January between the 1991-92 season and the multiyear averages are shown in Tables 4 to 6.

Table 4, which shows the number of days over the month in which the temperature falls below -20 and -25°C, indicates that for the winter of 1991/92, there were significantly fewer cold spells than usual. Table 5 indicates that the number of warm spells (temperature 0°C and above) was significantly higher for this winter. Finally, Table 6 compares the mean daily temperature and the standard deviation of the mean daily temperature. Surprisingly, the average daily temperatures for Point Claire during 1991-92 are only slightly greater than those for the longer term average, December being 0.6°C greater, and January 0.1°C greater. However, the most marked difference between the two periods is in the standard deviation of the mean daily temperature. They are significantly greater for the 1991-92 period than for the 8 year average for both December and January (6.4°C versus 2.1°C in December, and 7.5°C versus 2.7°C for January, for the 1991-92 and 8 year average respectively). Although the 1991-92 winter period appears to have had somewhat 'normal' monthly averaged daily air temperatures, there appears to have been unusually high variability in air temperatures during the period (again this is quite clear in the plot of daily air temperatures, Figure 12).

Table 4: Comparison of the number of days with low temperatures in December and January for this winter and a longer term average.

TEMPERATURE (°C)	DORVAL 1951-80		POINT CLAIRE 1991-92	
	December	January	December	January
-25°C and <	0.8	2.4	0.0	1.0
-20°C and <	3.6	7.0	0.0	3.0

Table 5: Comparison of the number of days with high temperatures in December and January for this winter and the longer term average.

TEMPERATURE (°C)	DORVAL 1951-80		POINT CLAIRE 1991-92	
	December	January	December	January
0°C and >	2.3	0.6	6.0	3.0

Table 6: Comparison of the December and January monthly mean daily temperatures and standard deviations of this temperature for this winter and a longer term average.

TEMPERATURE (°C)	MACDONALD COLLEGE 8 YR		POINT CLAIRE 1991-92	
	December	January	December	January
Mean Daily Temperature (°C)	-6.9	-10.4	-6.3	-10.3
Standard Deviation of Mean Daily Temperature (°C)	2.1	2.7	6.4	7.5

4.1.2 Wind

Wind speed and direction are important constraints on the source area for this study (ie. only winds from a select set of directions provide sensible heat fluxes from the required source, the water body).

The hourly averaged wind directions from the 4 meter tower are compared to those from MacDonald College (Canadian Climate Normals, 1987) for the 1969-80 period in Figure 13 while in Table 7 average wind speeds (in m s^{-1}) are compared for each month.

Table 7 a): Comparison of the average directional wind speed for the second half of November 1991 and the longer term average.

WIND DIRECTION (DEGREES)	WIND SPEED $(m\ s^{-1})$	
	Point Claire November 1991	MacDonald College November 1969-80
N	2.48	2.64
NE	3.36	3.89
E	1.99	2.97
SE	4.66	3.39
S	4.81	1.83
SW	4.56	4.81
W	4.95	4.39
NW	2.94	3.86

Table 7 b): Comparison of the average directional wind speed for December 1991 with the longer term average.

WIND DIRECTION (DEGREES)	WIND SPEED $(m\ s^{-1})$	
	Point Claire December 1991	MacDonald College December 1969-80
N	3.37	2.64
NE	3.94	4.53
E	2.96	2.92
SE	4.58	3.25
S	4.13	1.56
SW	3.68	4.92
W	3.35	4.59
NW	2.61	3.73

Table 7 c): Comparison of the average directional wind speed for January 1992 with the longer term average.

WIND DIRECTION (DEGREES)	WIND SPEED ($m\ s^{-1}$)	
	Point Claire January 1992	MacDonald College January 1969-80
N	3.24	2.59
NE	2.73	4.87
E	4.68	2.78
SE	4.23	3.31
S	2.82	1.86
SW	4.19	5.28
W	3.32	4.81
NW	1.89	3.06

Table 7 d): Comparison of the average directional wind speed for the first half of the month of February 1992 and the longer term average.

WIND DIRECTION (DEGREES)	WIND SPEED ($m\ s^{-1}$)	
	Point Claire February 1992	MacDonald College February 1969-80
N	3.59	3.17
NE	2.55	4.89
E	2.47	3.36
SE	1.60	2.42
S	1.80	1.67
SW	3.23	4.95
W	3.13	4.59
NW	2.38	3.14

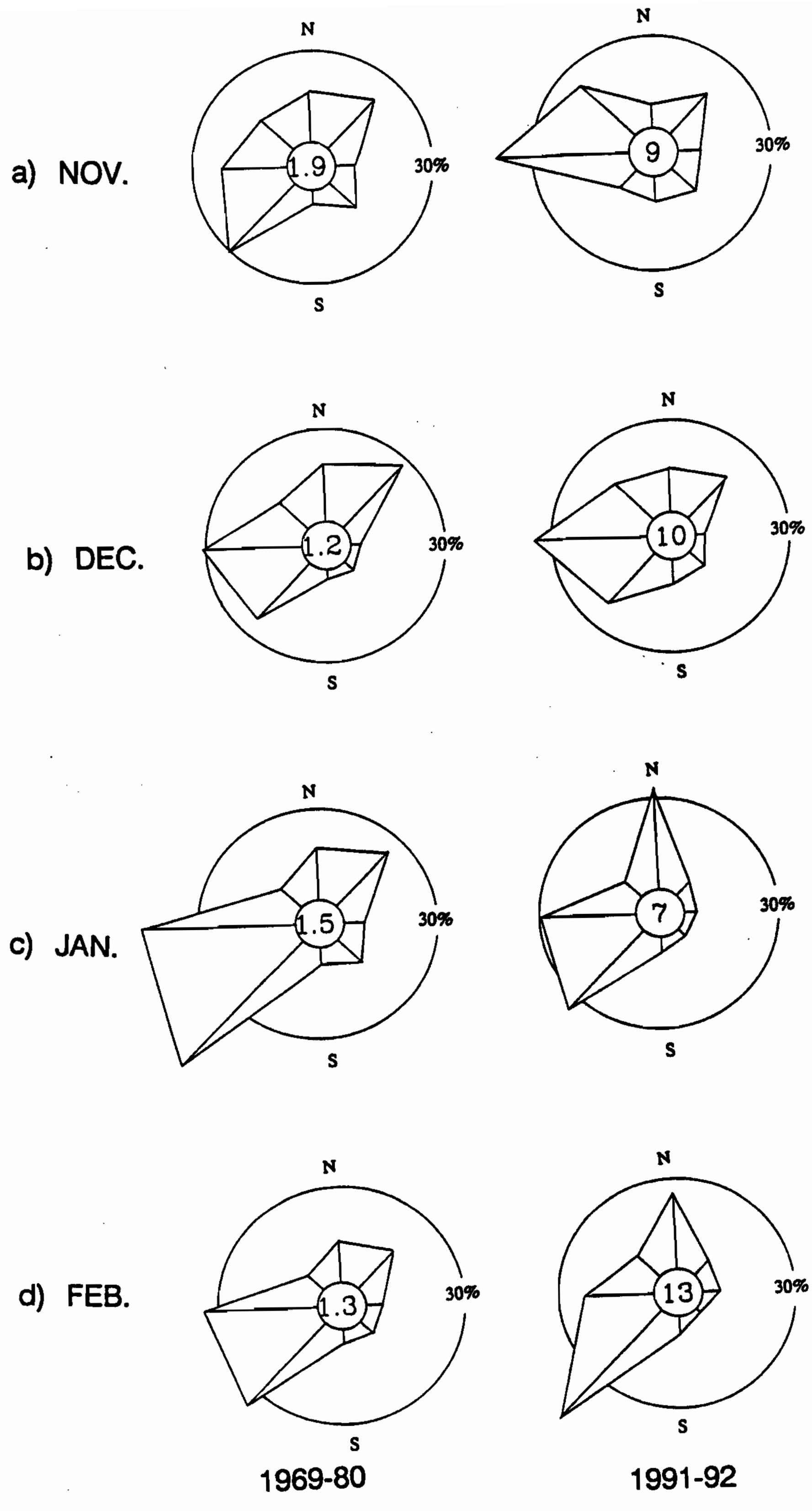


Figure 13: Comparison of monthly wind direction plots for 1991-92 and 1969-80.

The information for November (Figure 13 (a)) indicates a higher frequency of west and northwest winds and fewer southwest winds than the average. The other directions are similar. The average wind speeds (Table 7 (a)) in 1991 (calculated from 408 hours of data) appear to be similar. The directions with strongest wind are from the southerly quarter (with only southerly values deviating strongly from the 1969-80 average; the 1991 values having twice the average speed of the 1969-80 values).

The December (Figure 13 (b)) 1991 windrose (calculated from 744 hours of data) indicates values quite similar to the 1969-80 values. The average wind speeds in each direction (Table 7 (b)) indicates higher than average speeds for the southeast and south directions, and lower than normal speeds for the west and southwest directions.

The January (Figure 13 (c)) 1992 direction plots (calculated from 744 hours of data) indicate a lower than average frequency of west and southwest winds and higher frequency of northerly winds. The wind speeds for each direction (Table 7 (c)) indicate high wind speeds for the east southeast and southwesterly directions, and overall, values which vary somewhat from the 1969-80 average.

Figure 13 (d) shows the February 1992 directions (calculated from 328 hours of data) and indicates a slightly higher frequency of southwest and north winds compared to the 1969-80 average. The wind speeds (Figure 7 (d)) are above average for the north, west and southwest directions, however on the whole the 1969-80 averaged speeds are greater.

The percentage of calms in all months is much greater for the 1991/92 season than for the 1969-80 average. However, this may be a function of the instrument sensitivity and height above the ground. In some cases it may also be related to freezing rain (which can temporarily stop rotation of the anemometer).

The previous figures and discussion have indicated on a monthly basis what the dominant wind speeds and wind directions were for the 1991-92 measurement period. However, it does not take into account daily variations in wind direction. This is important as a reliable estimate of variations in the sensible heat flux due to an evolving ice cover depends on a period of persistant onshore winds. For the complete set of hourly wind directions, the daily maximum and minimum values were selected, the minimum values subtracted from the maximum value, and the average of the entire 91 day data-set averaged. The average maximum daily variation was 209.4 degrees, and the standard deviation was calculated as 123.7 degrees. Thus it is quite evident that there was a significant degree of variation in the wind direction within each day. As such, numerous days had source areas which could switch quite frequently from land to water. Although this left numerous gaps in the measurements of fluxes emanating from over water (or ice), it provided an interesting comparison of measurements over the differing surface areas.

4.1.3 Precipitation

The monthly precipitation totals for the months of November 1991 through to February 1992 indicate a few anomalies. The November 1991 average was the lowest on record, and the total precipitation for the month fell below the longterm average by close to 63 mm. Precipitation was predominantly in the form of rain. December, on the other hand, had a total precipitation only a few mm less than the long term average with slightly less recorded rain and more recorded snow than on average. January experienced 17 mm more precipitation than normal, with a much larger than usual proportion of rain. February was above the long term mean precipitation total with more snow and less rain than usual.

4.1.4 Ice and Snow Cover

As a result of the highly variable air temperatures over the 1991/92 winter (particularly with respect to periods in which the temperature rose to over 0°C, of which there were numerous occurrences after the initial ice cover formation) it is likely that the ice and snow cover fluctuated much more than normal. In fact, fluctuations from one day to the next were quite evident in the site visits.

Generally, the small area of water to the north of the 4 m tower remained ice covered throughout the majority of the winter due to sheltering. However, the area just to the south of the breakwater on which the 4 m tower was located tended to respond quite rapidly to changes in the air temperatures in conjunction with changes in wind direction and water velocity. There may be an increase in water velocity as a result of melting of snow and ice during these extreme warming periods. As a result, it was not uncommon for leads to develop that extended from the northwest to the northeast of the lake and following the northern shore of the lake (estimated to be on the order of 20-40 m in width) .

An examination of one of the few available maps on variations in the extent and thickness of ice on Lac St. Louis provides evidence of the rapidity to which changes in these variables can occur. The ice extents on various dates extending from late December to early February 1974/75 is shown in Figure 14. Although the ice during this winter season began to form at a much later date than the ice in the present 1991/92 winter, it is interesting to note how rapidly the ice cover responded to variations in air temperature. Ice cover formation began, in this 1974/75 winter on the northwest part of the lake, then extended along the northern shore and finally extended towards the channel situated to the south of the main lake body. There were five days in which the air temperature was below 0°C before the ice extended out from the northern shore of the lake on January 17. Within four days, when the air temperature remained below 0°C, the ice reached its greatest extent recorded for that winter on January 20th. After that date, although the temperature remained below 0°C, the eastern extent of the ice varied considerably. This provides evidence that more variables than just the air temperature (ie. wind speed, wind direction and water velocity) may play an important role in determining the extent of the ice cover over Lac St. Louis.

Although the same type of information is not available for the 1991/92 winter, information was collected during site visits of the extent and variability of the ice cover in the vicinity of the site. Again, as evidenced in the 1974/75 season, responses of the ice cover to variations in meteorological variables such as air temperature were very rapid. Two separate sets of visits showed the rapid formation or removal of ice to the south and southwest of the instrument towers. On 5 December 1991 there was a large

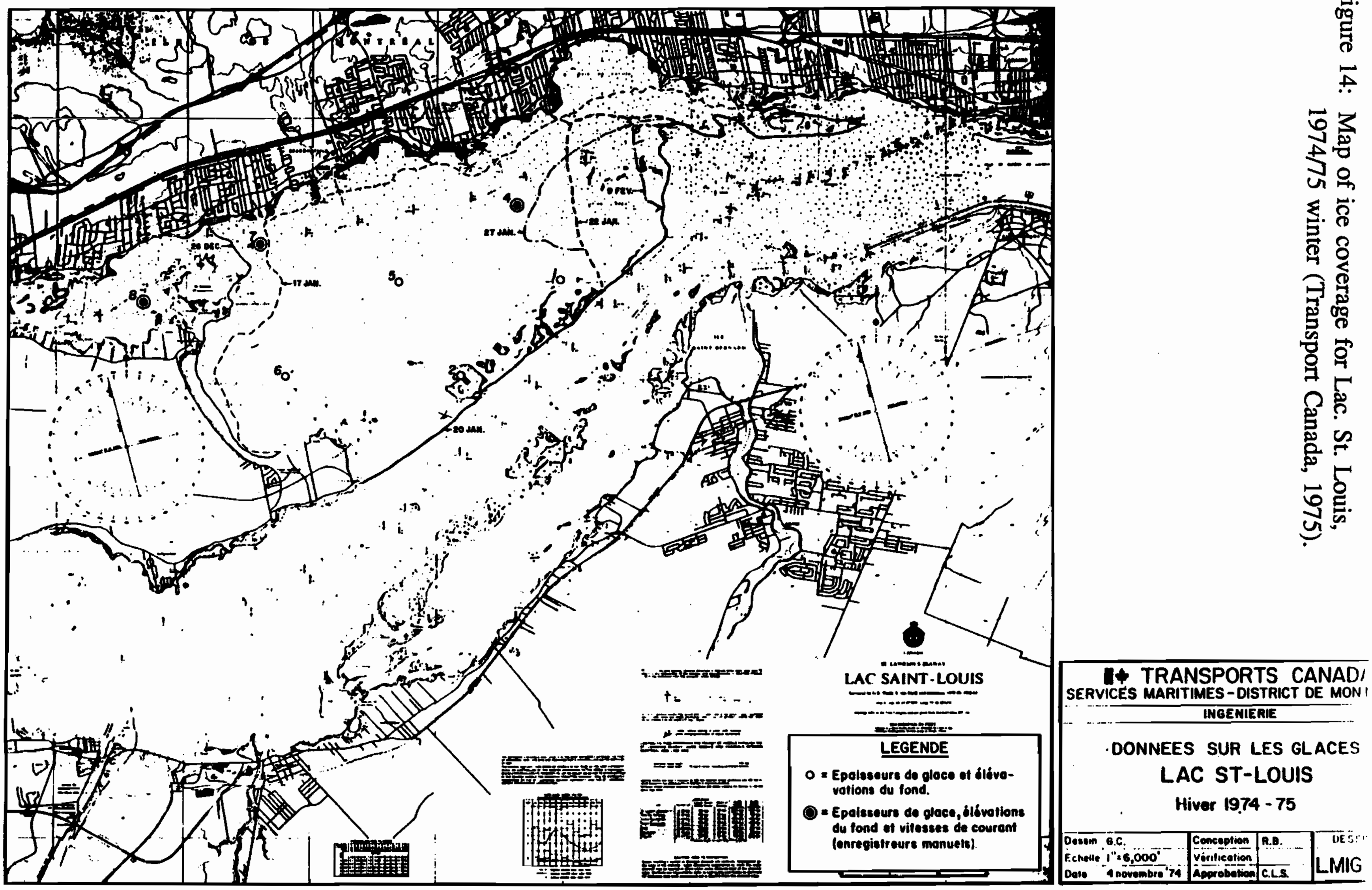


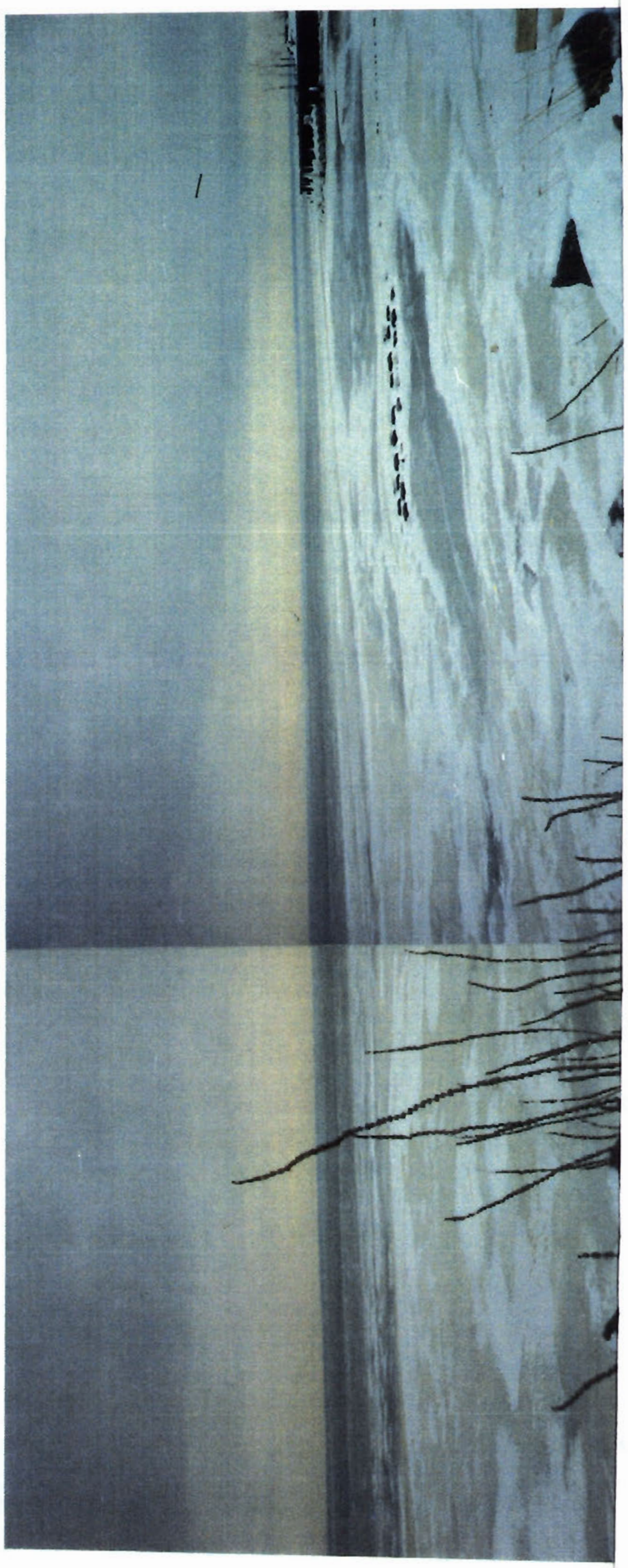
Figure 14: Map of ice coverage for Lac. St. Louis, 1974/75 winter (Transport Canada, 1975).

lead open to the south of the towers (again, estimated to be on the order of 20-40 m in width), and extending to the east and west, and 24 hours later on 6 December 1991 there was no open water visible. The same was observed to occur in reverse on another set of days, 20 and 21 December 1991, illustrated in Figures 15 and 16. On 20 December 1991 there was a complete ice cover with no visible water. Twenty-four hours later on 21 December 1991, a large expanse of water to the southwest and to the south of the tower was visible. This was a day in which the air temperatures rose slightly above 0°C, with an average air temperature of about 0°C for the day. There was however, a great deal of precipitation between the period of the two photographs with 1.6 mm in the form of rain, and 7 cm in the form of snow. Open expanses of water similar to that shown in Figure 16 were typical during the measurement period.

Two other sets of conditions which were quite common later in the winter are illustrated in Figures 17 and 18. Figure 17, taken on 27 January 1992 shows a complete ice cover, and a lake which was extremely windswept and hence had only a minimal and patchy snowcover. Figure 18 was taken towards the end of the measurement period on 15 February 1992, and represents conditions typical of that period in which the ice cover was extensive, and the snowcover deep and drifted.

As a result of the frequent warming periods and resulting periods of freezing rain and melts, the ice cover on the lake during the months of January and February was probably to a large extent made up of snow-ice (as opposed to black ice).

Figure 15: Lac St. Louis as seen from 4 m tower, 20 December 1991



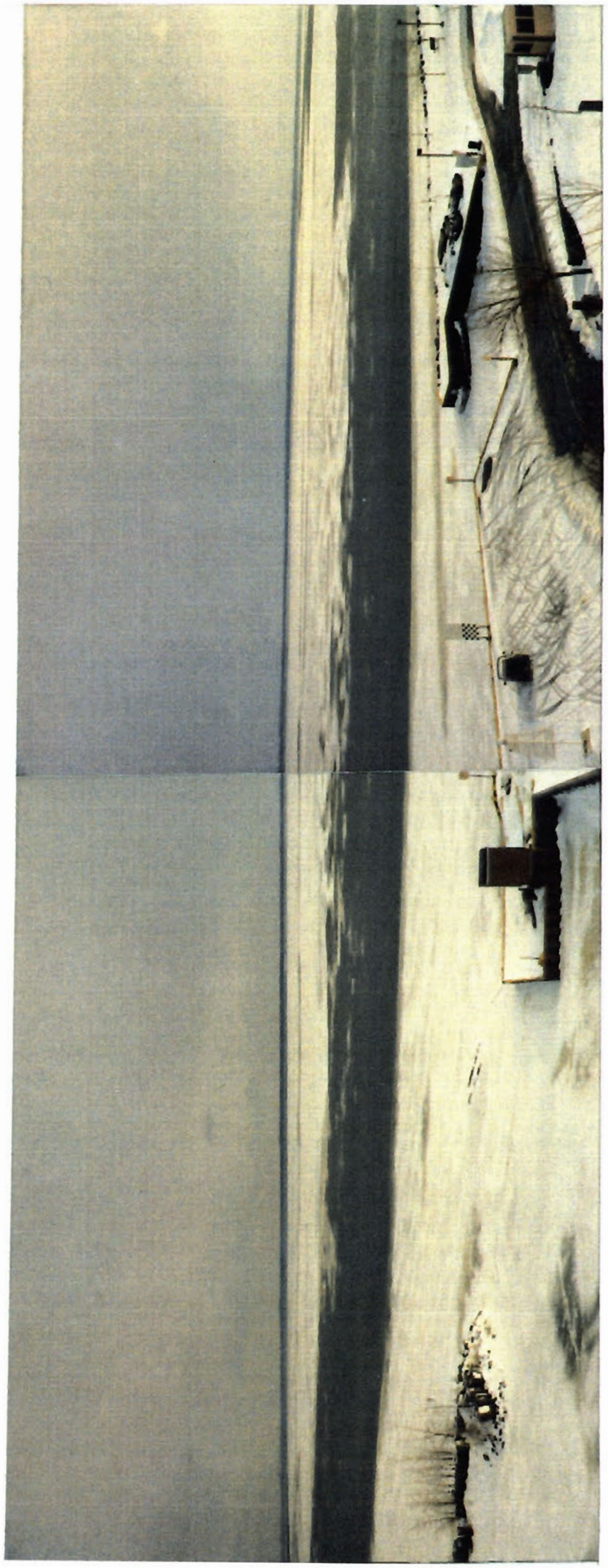
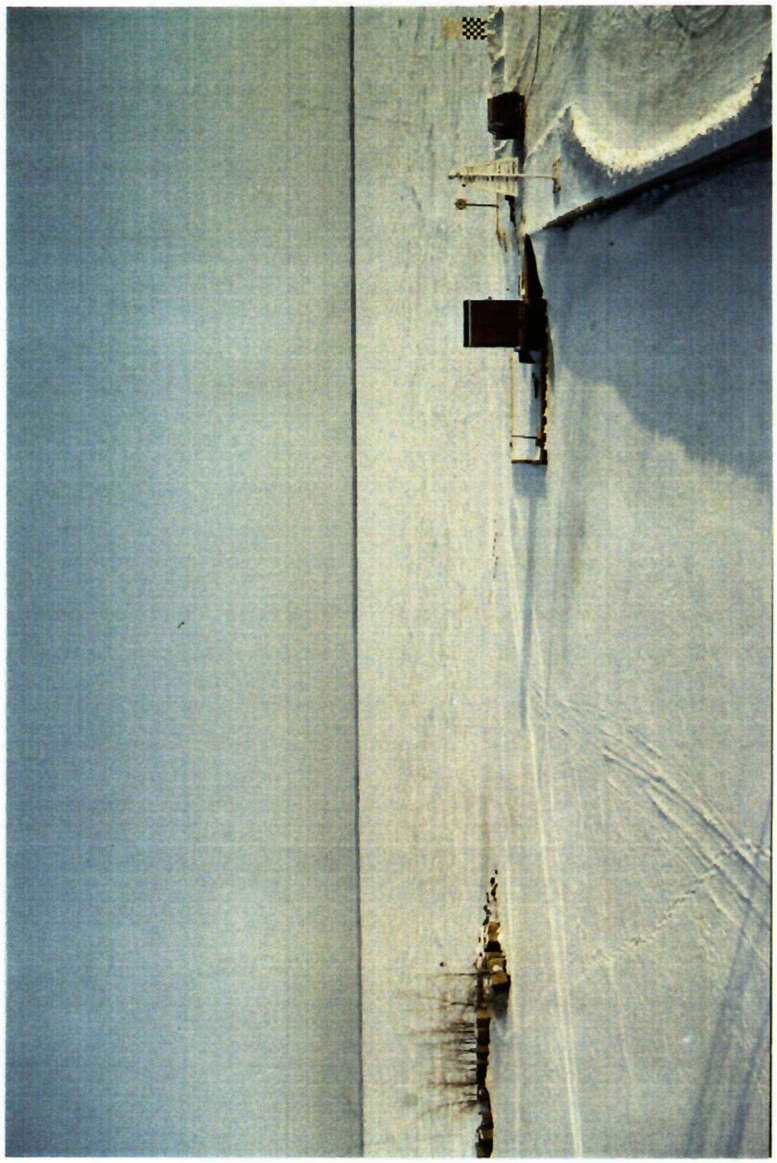


Figure 17: Lac St. Louis as seen from 17 m tower, 27 January 1992

Figure 18: Lac St. Louis as seen from 17 m tower, 15 February 1992



4.2 Instrument Evaluation

A major objective of this study was the evaluation of the instruments (particularly the eddy correlation instruments) as a means of obtaining a reliable set of longterm sensible heat flux measurements in a harsh physical environment. The following will provide a discussion on the sensible heat flux values obtained in relation to the broad meteorological patterns, problems with the installation of the equipment, and future recommendations.

4.2.1 Flux Magnitudes

A short statement regarding the magnitude of the raw heat fluxes is necessary in order to reiterate that they were, due to the method of instrumentation, probably being somewhat underestimated , particularly under stable conditions (see discussion in section 3.5.4). It is to be expected that, particularly before the period of freeze-up when there were warming periods and large influxes of heat into the water, the raw fluxes were in fact underestimations of the true values by approximately 50%, the remainder of the fluxes generally being underestimated by approximately 15%. Corrections were applied to all raw values with heat fluxes multiplied by a factor of 1.54 under stable conditions up until 3 December 1991 while all other values were multiplied by a factor of 1.15. Therefore, after 3 December 1991 corrected values may underestimate fluxes during stable conditions. However, as the magnitude of the fluxes was generally smaller after 3

December 1991 than before, the impact of the unknown stable periods is likely minimal.

4.2.2 Examination of the Data Record

The record of sensible heat flux and air temperature measurements is shown in Figure 19. The record of air temperature is important in the examination of the sensible heat flux values, as there tends to be a relationship between breaks in the sensible heat flux series and air temperature. Namely, when the air temperatures were close to 0°C and there was a precipitation event, there was often freezing rain accompanying it that broke the thermocouples.

Throughout the last two weeks of November and into early December (until about 3 December 1991), there were virtually no problems with the acquisition of heat flux data. However, once air temperatures dropped below 0°C, problems arose. The majority of 'gaps' in the series were a result of periods of rain, freezing rain, snow or some combination of those factors. The first example of this was on 3 December 1991, the second day in which the air temperature was well below 0°C, and a day in which there was both rain and snow (and presumably freezing rain in the transition) recorded. Placement of a second Gill/thermocouple system on the 17 m tower onshore on 6 December 1991 was shortlived, as 7 December 1991 produced a large snowfall, again halting operation of the system. On 8 December 1991 the system began operating again and remained in operation until 13 December 1991 on which there was a significant recorded rainfall. Replacement of the thermocouples on both the 4 m and 17 m tower

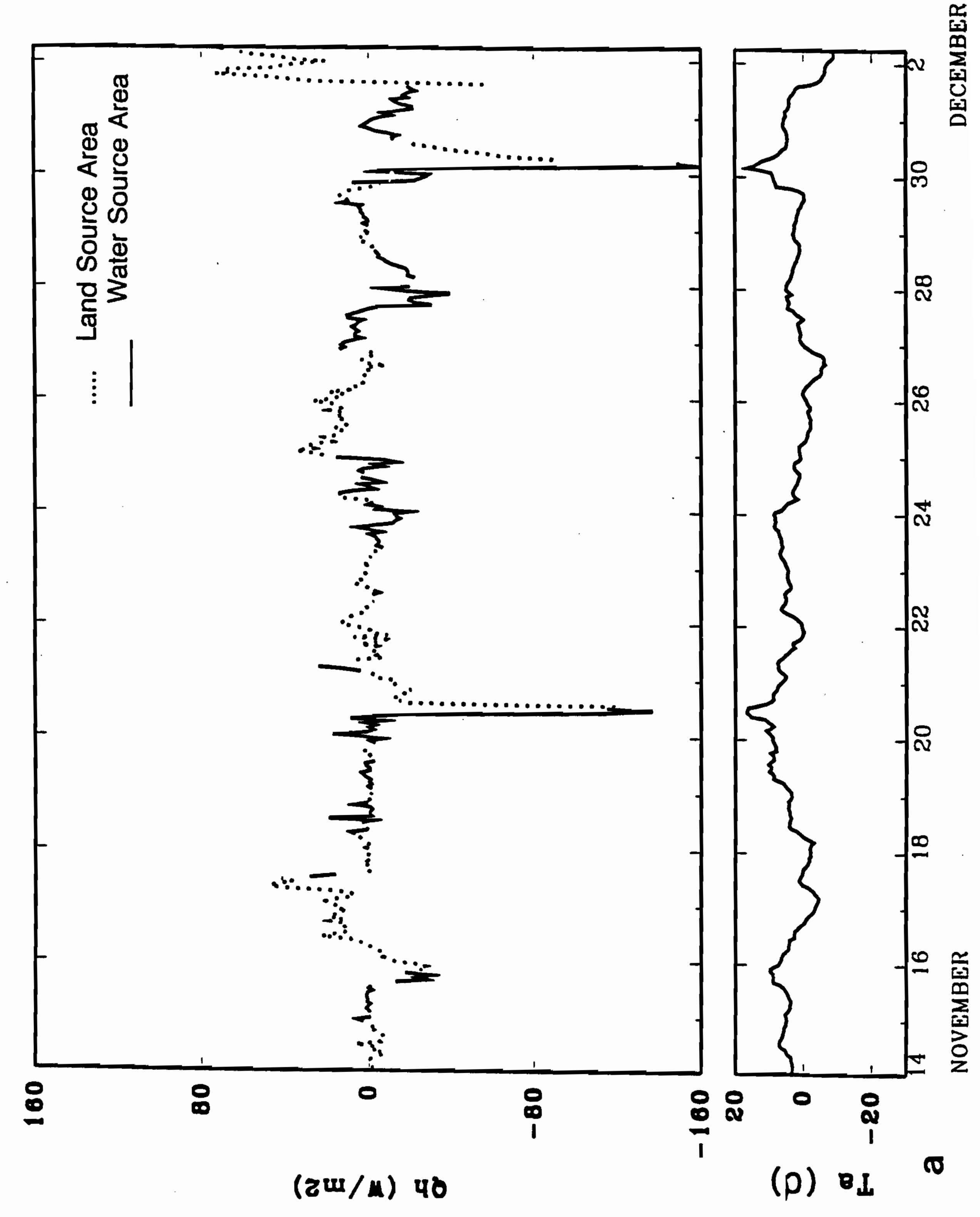
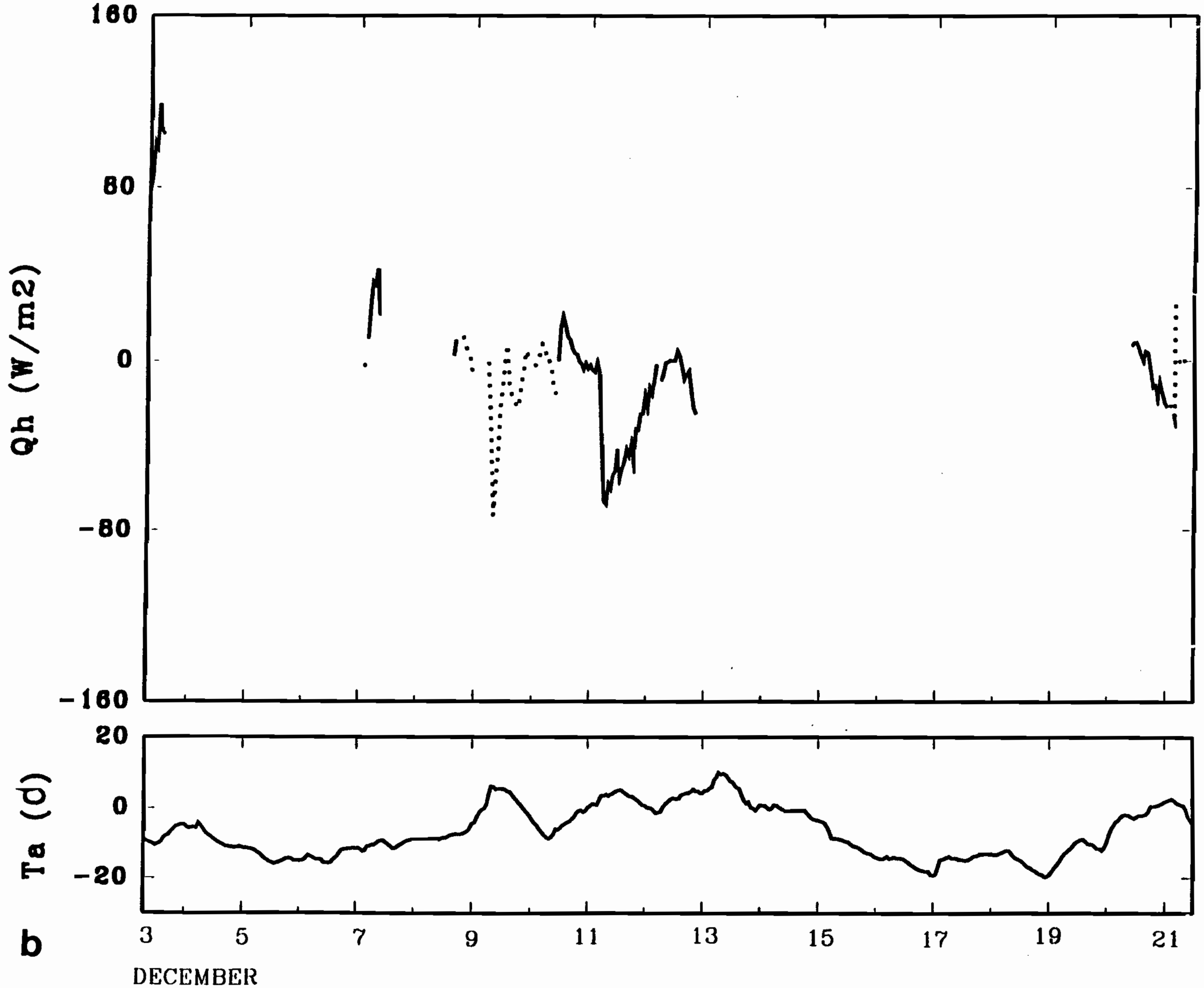
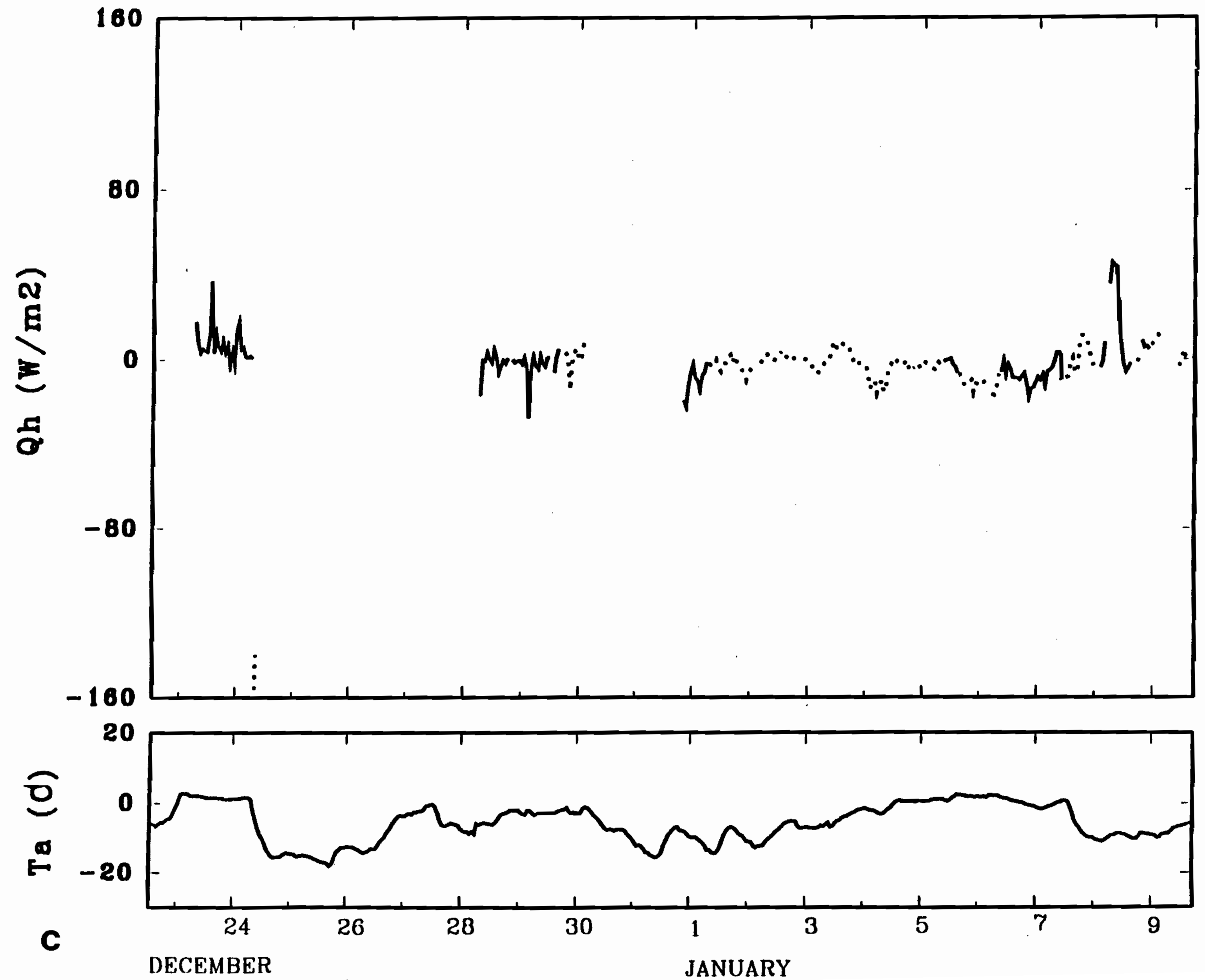
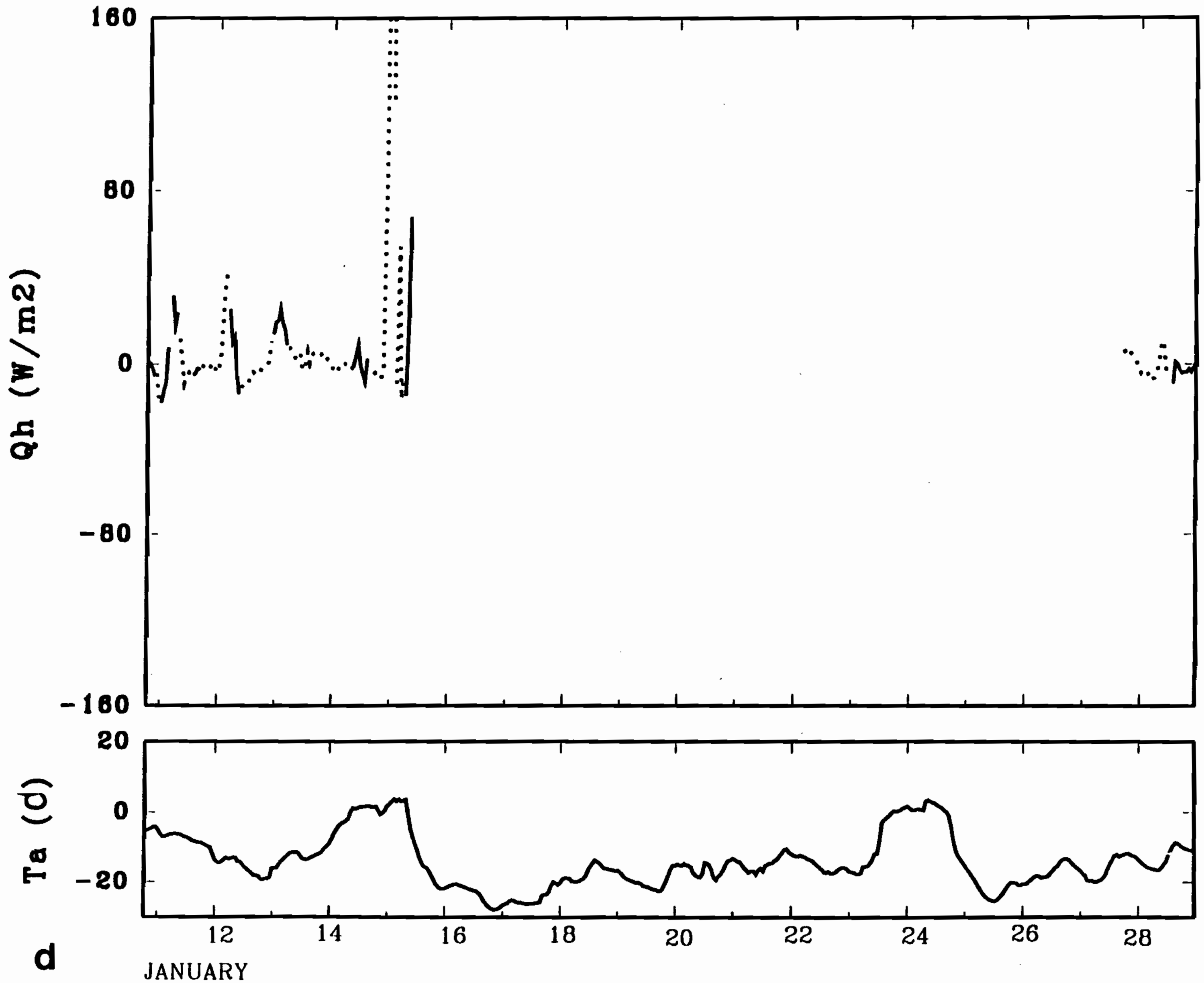


Figure 19: Entire set of sensible heat flux and air temperature measurements for Lac St. Louis, winter 1991/92.

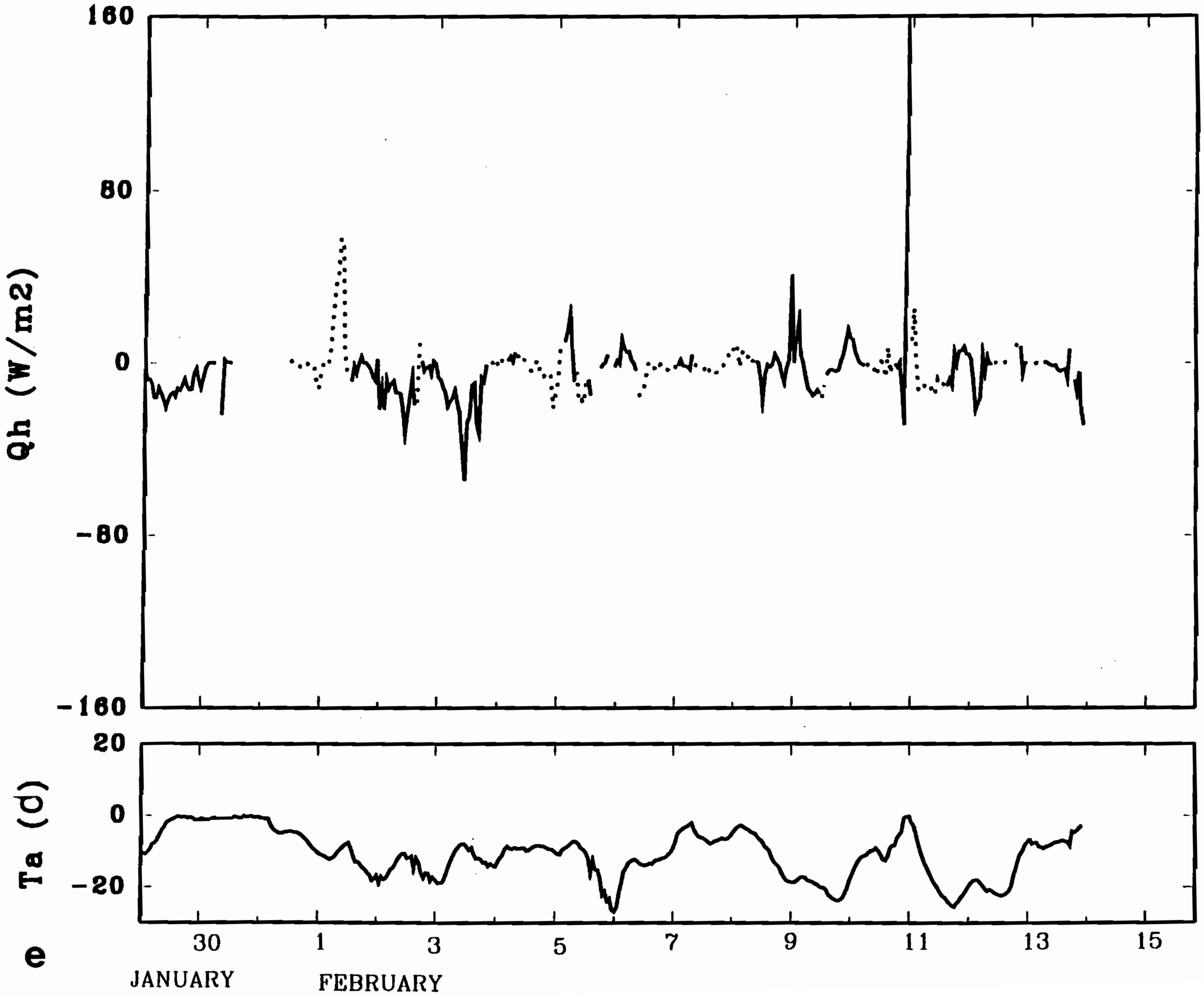


b


160
80
0
-80
-160
Qh (W/m2)
20
0
-20
Ta (C)
24
26
28
30
1
3
5
7
9
DECEMBER
JANUARY
C



d


Qh (W/m2)
160
80
0
-80
-160
Ta (C)
20
0
-20
30
1
3
5
7
9
11
13
15
JANUARY
FEBRUARY
e

during a site visit on 17 December 1991 was not possible, as conditions were unsafe for crossing the ice, and it was too windy to mount the 17 m tower. Replacement on 20 December 1991 of the thermocouples on the 4 m tower provided intermittent measurements until replacement of the thermocouples on the 17 m tower on 31 December 1991 (this set of intermittent measurements will be discussed further below). After 13 December 1991 all sensible heat flux measurements were made from the 17 m tower. From this point until 14 January 1992, a day in which 25 mm of rain was recorded, the measurements were continuous. Again, replacement of a thermocouple on the 17 m tower (the second chromel-constantan wire was broken and appeared to be giving intermittent measurements) on 27 January 1992 provided an almost continuous set of measurements until the end of the measurement period on 15 February 1992, with problems evident only for a short period on 30 and 31 January 1992. This was likely due to freezing rain on 30 January 1992 which may have halted rotation of the Gill propeller for a couple of days, producing unrealistically small heat flux values.

There were a number of cases in which there were intermittent measurements (ie cases in which there was a break in the sensible heat fluxes recorded with the continuation of the measurements without replacement of thermocouples). For many of the relatively short breaks of only a few hours or a day, the breaks may have been due to a shorting out of the terminals when they got wet, as they seemed to occur for the most part, on days in which there was a precipitation event. Examples include 7 December 1991, 7, 9, and 30 January 1992. The cause in other cases may have been freezing of the vertical propeller which resulted in a heat flux of 0 W m^{-2}. Those breaks which occurred on the 4 m tower between 20 and 30 December 1991 were likely a result of breakage of the chromel-constantan wire connecting the thermocouples to the datalogger.

Another indication of problems with the use of this instrumentation is evident on two occasions when the recorded sensible heat fluxes were unrealistically large. On 14 January 1992 the peak (uncorrected) value was 449 W m^{-2}, while on 11 February 1992 it was 376 W m^{-2}. Both periods were meteorologically similar (although the source areas were different) in that they occurred when there was an air temperature increase to close to or just over 0°C, and some form of precipitation. On 14 January 1992 the air temperatures increased to almost 3°C and there was 25.5 mm of rain recorded. On 11 February 1992 the air temperatures rose to -0.36°C, and there was 4.3 cm of snow recorded.

In addition to problems with the sensible heat flux measurements, there were related problems with the atmospheric stability measurements. Aside from the fact that there was an extensive time lapse after commencement of the initial freeze-up and the time in which it was safe to walk over the ice to the 4 m tower, the cable running from the Gill to the data logger was damaged by an attempt to resecure the upper part of the tower which had become loose.

4.2.3 Causes of Instrument Problems

There were numerous problems with the acquisition of the data, particularly the sensible heat flux data. These problems were not all a result of the instrumentation, but included logistical problems. These included such problems as unfavourable weather conditions which made driving to the site unsafe, and frequent warming periods which made traversing the ice to the 4 m tower on the breakwater impossible for safety reasons. Another consequence of the numerous warm periods, which resulted in freezing rain events, sudden melts and sudden refreezing, included the buildup of a large amount of ice at the bottom of the 4 m tower which made lowering the tower, and hence replacing and fixing the instruments virtually impossible.

Problems with the acquisition of the sensible heat flux data as a result of the instruments used in this environment were mainly associated with the thermocouples. The Gills were fairly reliable, the only problems encountered being with the destruction of the propellers by sea gulls during the testing period, and occasional freezing (generally due to freezing rain) of the propellers which halted rotation for a short time. The thermocouples however, due to the fact that the wire was extremely thin and fragile and it was necessary that they be unshielded and unprotected, were frequently broken (generally at the thermojunction) as a result of high winds, heavy rainfalls, freezing rain, and heavy snowfalls. There also appears to have been problems with permanent breakage of the chromel-constantan wire connecting the thermocouples to the datalogger (three of the four wires on the two towers were giving intermittent results by the end of the measurement period), probably as a result of low temperatures.

4.2.4 Recommendations

The numerous problems encountered with the attempts to get a complete series of winter sensible heat flux estimates over Lac St. Louis were in part a result of the anomalous weather which resulted in the numerous periods of freezing rain, and the continual degradation and reformation of the ice cover. Regardless of that fact, it is quite clear that many of the problems, (particularly with the thermocouples) would be likely to occur during other winters; the conditions are too harsh and the thermocouples too fragile to withstand the conditions. The numerous other studies which have employed the use of this eddy correlation system were conducted in less harsh environments, and hence few problems were encountered with breakage of the thermocouples. Although this site was advantageous from the point of view that underestimation of the fluxes by the propellers as a result of low wind speeds was likely minimal, the system was too limited by the fragility of the thermocouples to make infrequent visits and remote monitoring viable. This problem might be alleviated somewhat if the thickness of the thermocouple wire was increased; however, tests would have to be run to ensure that the loss in sensitivity would be minimal. For systems used in very cold environments, it is recommended that the chromel-constantan wire connecting the thermocouples to the data logger be insulated, so as to prevent snapping of the wires due to the cold air temperatures.

CHAPTER 5

SENSIBLE HEAT FLUXES: TEMPORAL VARIATIONS AND CONTROLS

5.1 Overview of Data

The series of data collected was not continuous; a result of changing wind directions (ie. the source area was not always from over the lake), and intermittent equipment problems. The changes in wind direction were expected, and the project was designed with the understanding that only a segment of the data collected would originate from the required source area. Many of the equipment problems, on the other hand, were not anticipated. Problems arose due to rain, freezing rain or snowstorms in which the thermocouple wire was often damaged and propellers occasionally frozen or broken.

The conditions over the period of this study were less than ideal in the sense that there was not a single period of freeze-up. Instead, (as has been discussed to some degree in Chapter 4) there were numerous periods of warming and cooling, and hence ice cover formation and degradation. This presented problems when it came to examination of days representative of periods prior to, during, and after ice cover formation. Thus, although it did not provide a single freeze-up period, the winter of 1991/92 permitted observations under continually varying conditions, and allowed for observation of the rate at which the source water body responded to changes in meteorological conditions.

This section will present a series of case studies in the form of daily plots of the hourly sensible heat flux variations (in conjunction with hourly air temperature and horizontal wind speed plots) in order to investigate the effect of meteorological and ice conditions on the magnitude of sensible heat fluxes. Figure 20 ((a) to (e)) is a plot of the entire (intermittent) series of sensible heat flux measurements and meteorological variables. The objective of this figure is to provide a summary of most of the meteorological conditions throughout the measurement period. The sensible heat flux and temperature series are available in Figure 19 ((a) to (e)) on a more detailed plot. However, Figure 20 ((a) to (e)) provides those two variables along with the horizontal wind speed, relative humidity, number of daylight hours in which there was sunshine (as a % of the total daylight hours), and precipitation in the form of rain (mm) and in the form of snow (cm). The sensible heat flux, air temperature and horizontal wind speeds are plotted hourly, while the relative humidity, sunshine and precipitation variables are represented by single daily values. Note has also been made on the plots of known periods of ice cover formation or ice cover degradation, and the dates of the case studies discussed in this chapter.

5.1.1 Measurement Errors

Before making a detailed examination of the sensible heat flux information obtained in this study, it is important to discuss all the potential errors associated with

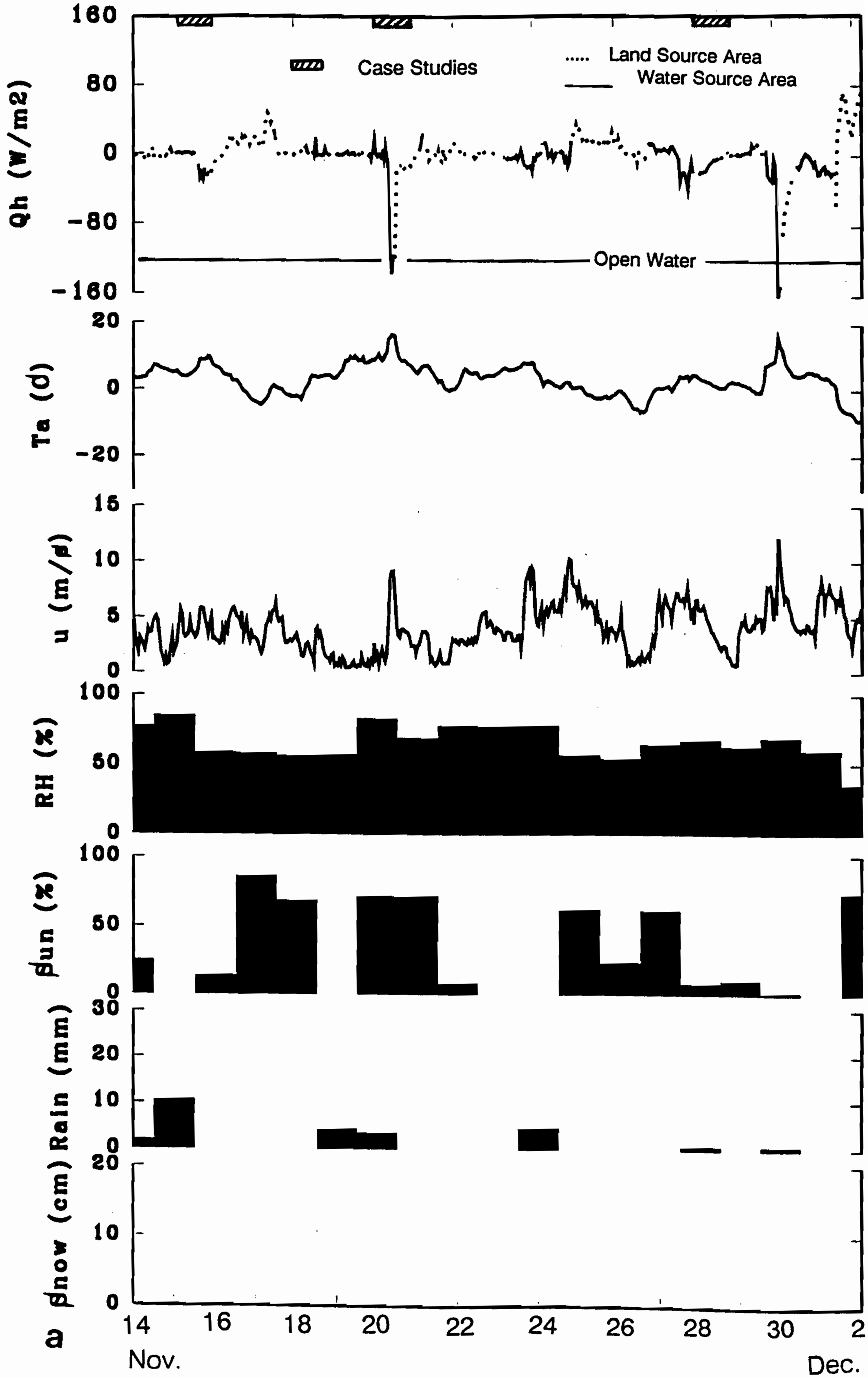
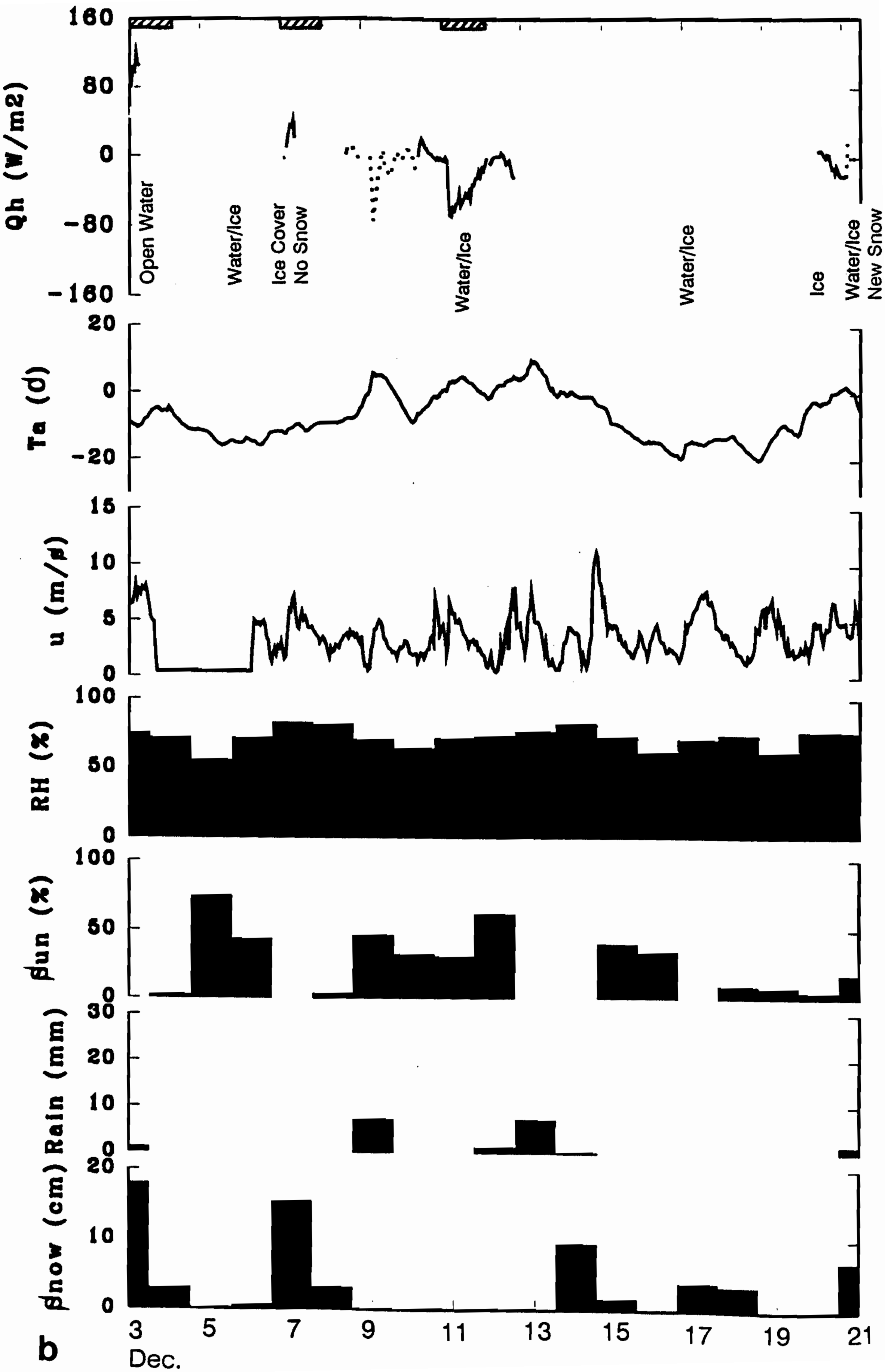
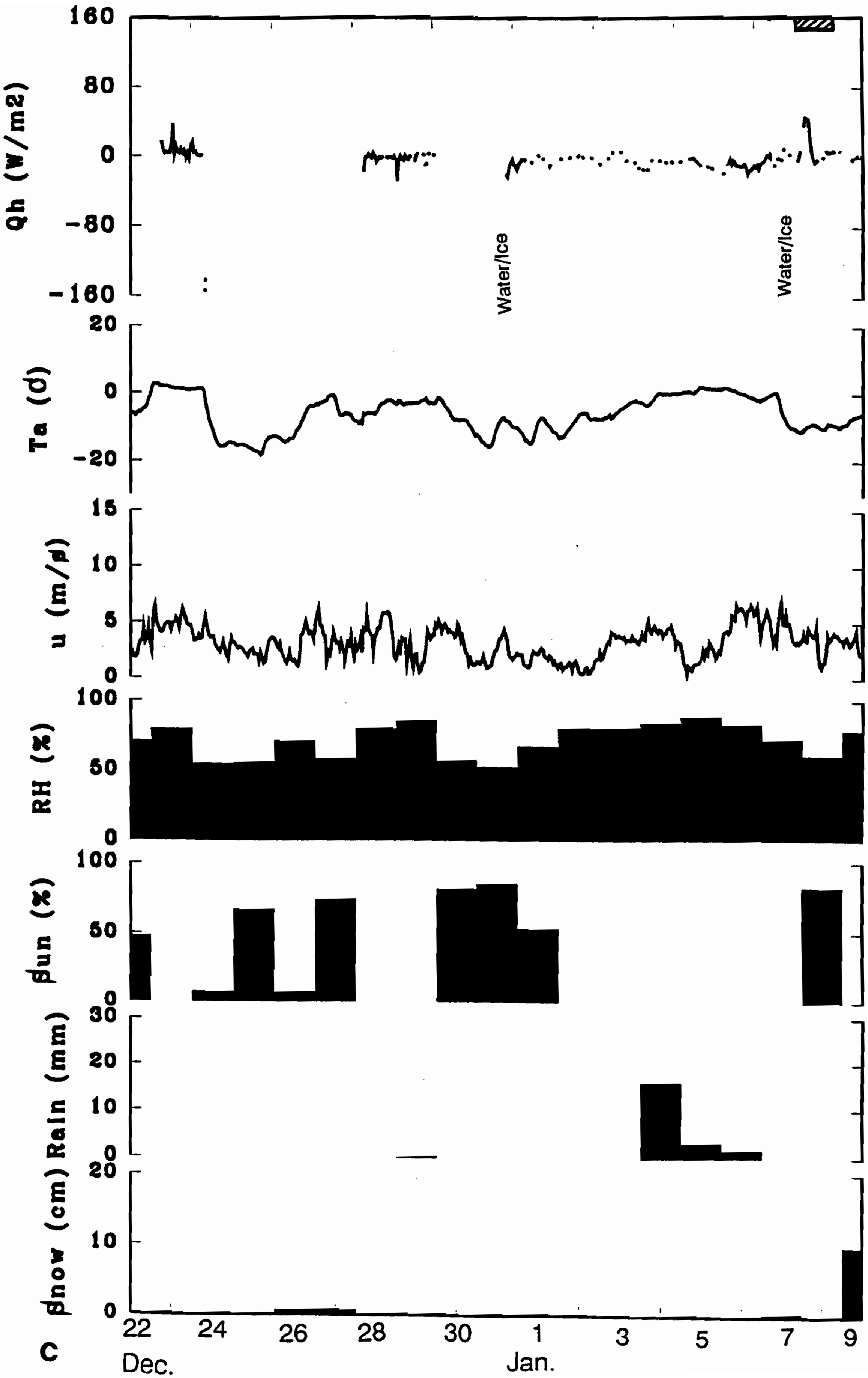


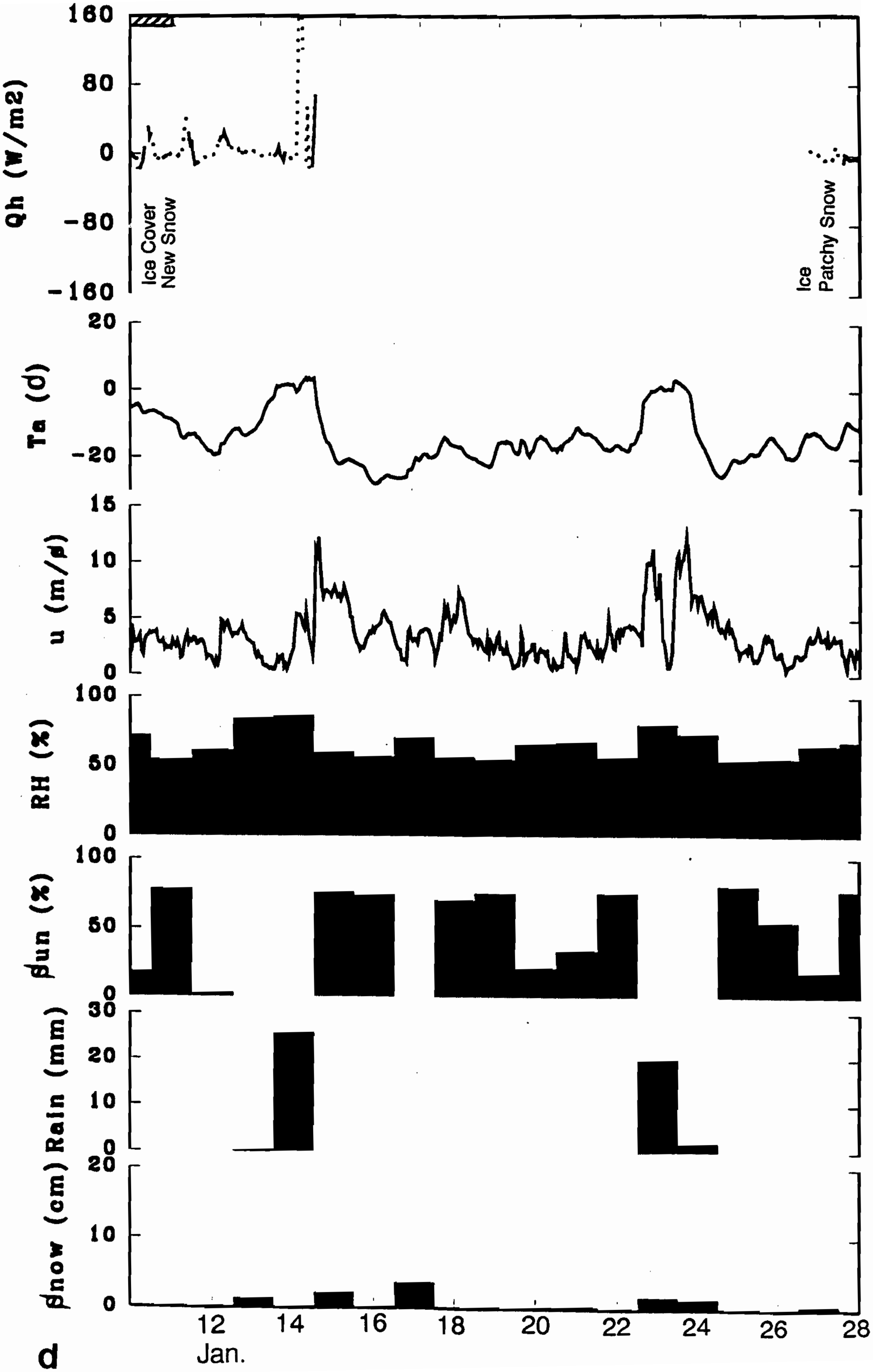
Figure 20: Sensible heat fluxes and meteorological variables for Lac St. Louis.



Qh (W/m2)
160
80
0
-80
-160
Open Water
Water/Ice
Ice Cover
No Snow
Water/Ice
Water/Ice
Ice
Water/Ice
New Snow
Ta (C)
20
0
-20
u (m/s)
15
10
5
0
RH (%)
100
50
0
Sun (%)
100
50
0
Rain (mm)
30
20
10
0
Snow (cm)
20
10
0
3
5
7
9
11
13
15
17
19
21
Dec.
b

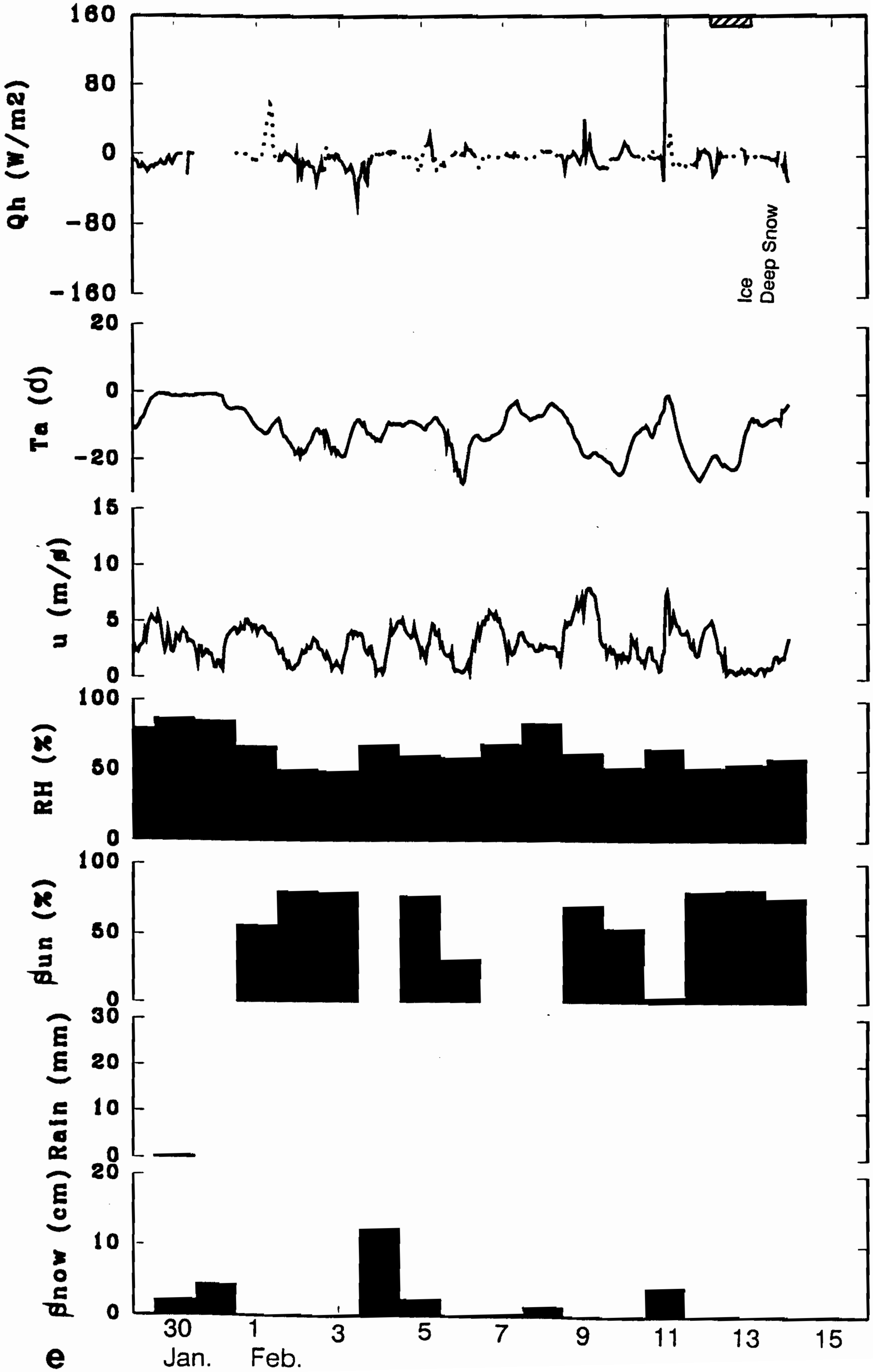

Qh (W/m2)
160
80
0
-80
-160
Water/Ice
Water/Ice
Ta (C)
20
0
-20
u (m/s)
15
10
5
0
RH (%)
100
50
0
Sun (%)
100
50
0
Rain (mm)
30
20
10
0
Snow (cm)
20
10
0
22
24
26
28
30
1
3
5
7
9
Dec.
Jan.

C



160
80
0
-80
-160
Qh (W/m2)
Ice Cover
New Snow
Ice
Patchy Snow
20
0
-20
Ta (C)
15
10
5
0
u (m/s)
100
50
0
RH (%)
100
50
0
Sun (%)
30
20
10
0
Rain (mm)
20
10
0
Snow (cm)
12
14
16
18
20
22
24
26
28
Jan.

d


Qh (W/m2)
160
80
0
-80
-160
Ice
Deep Snow
Ta (C)
20
0
-20
u (m/s)
15
10
5
0
RH (%)
100
50
0
Sun (%)
100
50
0
Rain (mm)
30
20
10
0
Snow (cm)
20
10
0
30
1
3
5
7
9
11
13
15
Jan.
Feb.

e

these measurements.

The measurements have two types of associated errors: random errors and systematic errors. Random errors are those which generally arise as a result of natural variability. Essentially, this set of sensible heat flux measurements is being presented as values representative of the sensible heat fluxes over Lac St. Louis under the various meteorological and source area conditions experienced at the time the measurements were recorded. However, instrument error aside, this is not necessarily the 'true' sensible heat flux for this water body over this period of time. Simultaneous measurements of off shore flow made over the same interval with identical eddy correlation systems would not produce identical results. Without the resources available to monitor these variations it is impossible to know how representative the resulting heat flux measurements are. Therefore the question of how representative this single set of measurements is of the entire water body should be kept in mind. As an example, the pre-field tests (discussed in section 3.5.5) yielded an average difference in sensible heat fluxes over a continuous 224 hour period of just under 1.5 W m^{-2} for a single Gill with two different thermocouples (on the order of 20 cm apart), attached to a CR10 datalogger. It is anticipated that this error to a large extent is related to natural variability.

The systematic error on the other hand will result in a set of measurements which are consistently low or high (Fritschen and Gay, 1979). In the case of the Gill/thermocouple system used in this study, the errors are generally associated with a lack of sensitivity of the Gill propeller anemometer (discussed in Chapter 3). Use of this instrument results in a systematic underestimation of the sensible heat flux values. The major factor contributing to this underestimation is the cosine response, which can produce underestimations in the wind speed measurements of up to 12%. In addition there is a +/- 1% correction when converting from rev cm^{-1} to m s^{-1}, as well as a probable error associated with the calibration of the individual instruments. Other potential sources of instrument errors include further underestimations by the Gills with low wind speeds, misalignment of the Gills with respect to the measurement surface, and a potentially non-uniform (ie non-horizontal) measurement surface (these last points, as pointed out in Chapter 3, are expected to have been to some degree minimized by the flat surface and relatively high wind speeds). The thermocouples, although having a substantial error associated with absolute temperature measurements, (see section 3.5.4), have a 0.003 s time constant. As these thermocouples were not used to obtain absolute temperature measurements, but only the temperature fluctuations (sampling at a rate of 0.1 s), the associated error is expected to be minimal.

Attempts have been made to correct for the underestimations by comparing the Gill/thermocouple system with sonic anemometers (Amiro and Wuschke, 1987; Amiro et al., 1988; Horst, 1973). This study followed corrections made by Amiro and Wuschke (1987); the application of a multiplication factor of 1.15 for unstable and neutral conditions, and of 1.54 for stable conditions. As stability was not available for any case studies after 3 December 1991, the sensible heat fluxes may be underestimated (based on this set of corrections) by 25% (ie when conditions are stable only a 1.15 correction factor was applied rather than a 1.54 correction factor).

It is hoped that by employing the use of the eddy correlation technique, a large step has been taken in terms of alleviating measurement errors (ie versus the commonly used aerodynamic approach). However, it is clear from the above discussion, that the potential for large errors in the measured values still exists, particularly as a result of underestimations by the Gill. Although corrections were applied, there is still expected to be instrument error (particularly after the loss of atmospheric stability information), and an error associated with the natural variability of the measurement surface.

5.2 Case Studies

In order to observe certain periods in more detail, a series of case studies will be presented in this section based on 24 hour periods (these cases are summarized in Table 8). In addition to the sensible heat flux, the air temperature and horizontal wind speeds will also be illustrated. Synoptic weather maps of the case study days (as well as the days just prior to and after these case study days) are included in Appendix 4. These case studies will focus on heat exchanges under the various lake surface conditions encountered during the measurement period (these are shown in Figure 20 (a) through (e)). Cases will be drawn from periods before ice cover formation, after initial ice cover formation, periods following the initial ice cover period in which there was a continual removal and reformation of the ice cover, and a period later in the winter in which there was a thick and stable ice cover with a deep drifted overlying snowpack. The case studies will be compared and analyzed further after the individual cases have been introduced and discussed.

Table 8: Summary of selected case studies.

CASE STUDY	DATE	WATER BODY CONDITIONS	DISTINCTIVE CHARACTERISTICS
1	November 15 1991	Open water	-maximum Q_h exchange of approx. +30 W m^{-2} -response of Q_h to changes in windspeed
2	November 20 1991	Open water	-maximum Q_h exchange of approx. -145 W m^{-2} -very variable air temperature and windspeed during day
3	November 28 1991	Open water	-maximum Q_h exchange of approx. -40 W m^{-2} -fairly stationary air temperature and windspeeds
4	December 3 1991	Open water (just prior to ice cover formation)	-maximum Q_h exchange of approx. +120 W m^{-2} -negative air temperature and high windspeeds
5	December 7 1991	Ice cover (just after complete ice cover formation)	-maximum Q_h exchange of approx +45 W m^{-2} -low air temperature
6	December 11 1991	Partial ice cover	-maximum Q_h exchange of approx. -70 W m^{-2} -warm atmosphere
7	January 8 1992	Partial ice cover	-maximum Q_h exchange of approx. +45 W m^{-2} -cold atmosphere
8	January 10 1992	Complete thin ice cover and fresh thin snowcover	-maximum Q_h exchange of approx. +30 W m^{-2} -cold atmosphere
9	February 12 1992	Thick ice cover and deep drifted snowcover	-maximum Q_h exchange of approx. -20 W m^{-2} -cold atmosphere

In the case studies in which there were short gaps in the flux values (of a few hours), a spline fit was made. Data missing at the start or the end of the day was not estimated. These fluxes are shown in the following manner: a positive flux represents surface to atmosphere exchange, and a negative flux represents atmosphere to surface exchange.

5.2.1 Open Water

The period leading up to the initial ice cover formation extended from 14 November 1991 through to 3 December 1991, when air temperatures were generally greater than 0°C. The period demonstrates the response of the water body to changes in air temperature and wind speed, and the characteristic magnitude of the fluxes in the absence of ice-coverage. A limitation (not unexpected) of this series of data is that generally the periods through which the temperatures are decreasing coincide with a shift of the winds from southerly directions to northerly directions (ie. the winds tend to flow off-land with shifts to lower air temperatures, and hence the over-water sensible heat fluxes are unrecorded).

5.2.1.1 15 November 1991

Despite the relatively small sensible heat fluxes this day provided an examination of the response of the water body to variations in the horizontal wind speed. Montreal was influenced on 15 November 1991, by the passage of a low pressure system and an accompanying warm front. Throughout this day the sky was overcast with some precipitation in the form of rain (10.5 mm), and a relative humidity of 85%. The sensible heat fluxes throughout this day were virtually negligible until 1600 hours (Figure 21). Before 1400 hours the air temperature remained between 3 and 5 °C, and not until later in the afternoon when the air temperatures rose to between 7 and 10 °C did the sensible heat flux increase in magnitude, approximately to -30 W m^{-2} into the water. There was also a heat flux response to an increase in wind speed (of over 5 m s^{-1}) during this late afternoon period. However an earlier period of increased wind speeds (also greater than 5 m s^{-1}) appeared not to have any affect on the low sensible heat flux values.

5.2.1.2 20 November 1991

20 November 1991 was characterized by an extremely large influx of heat into the water body during the afternoon (Figure 22). This same pattern was also evident on 30 November 1991. The period between 15 November 1991 and 20 November 1991 was marked by a drop in the relative humidity and by a drop in average air temperature to just below 0°C (during which there was likely a net heat loss). Following this was a steady air temperature increase during which the fluxes remained close to 0 W m^{-2}. The day of 19 November 1991 which had an average air temperature slightly greater than 15 November 1991 contributed very little to the sensible heat exchange (possibly due to the unusually low wind speeds which averaged 0.92 m s^{-1} for the day). 20 November 1991

Figure 21: Plot of sensible heat flux, air temperature and horizontal windspeed for 15 November, 1991.

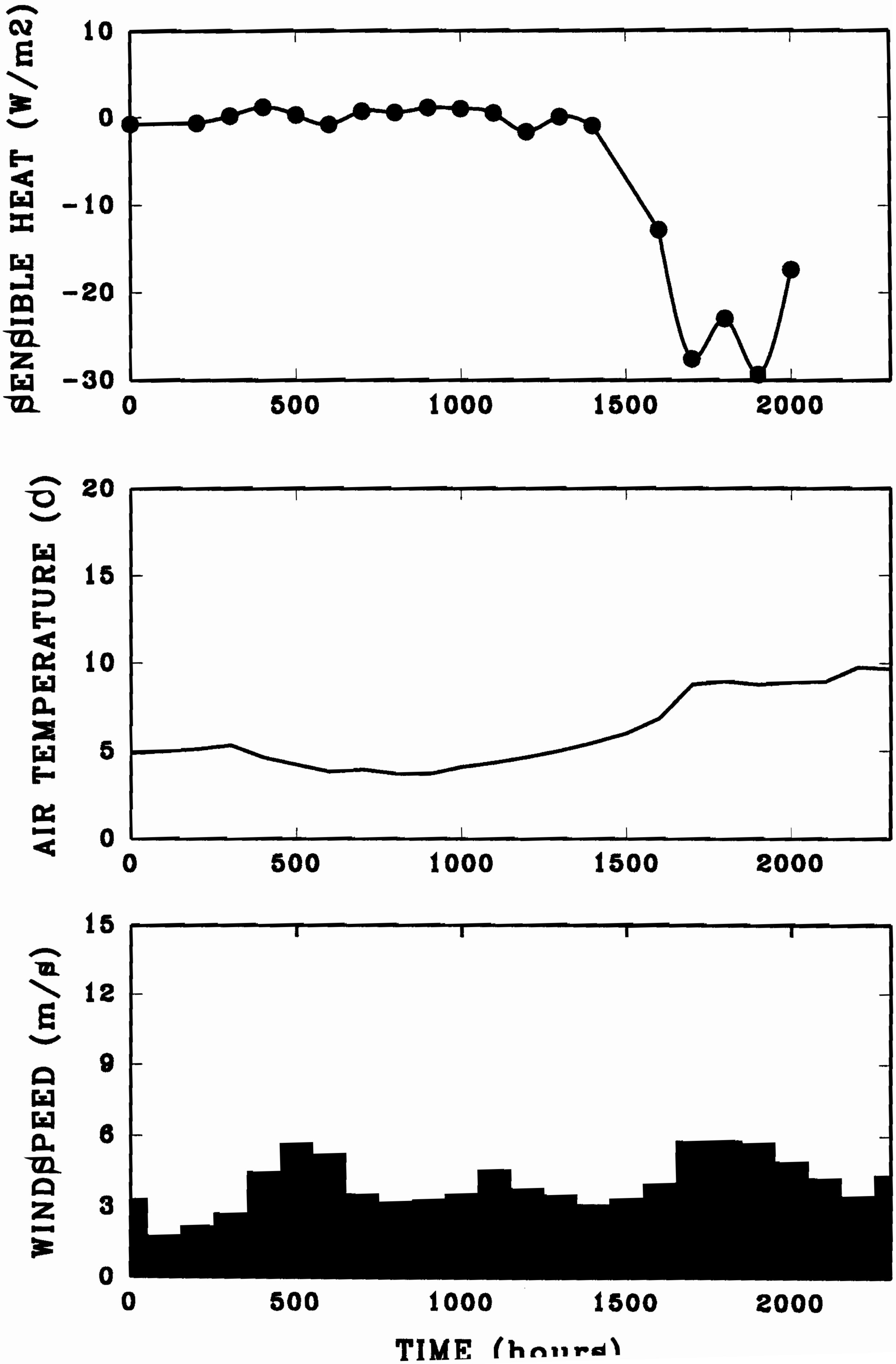
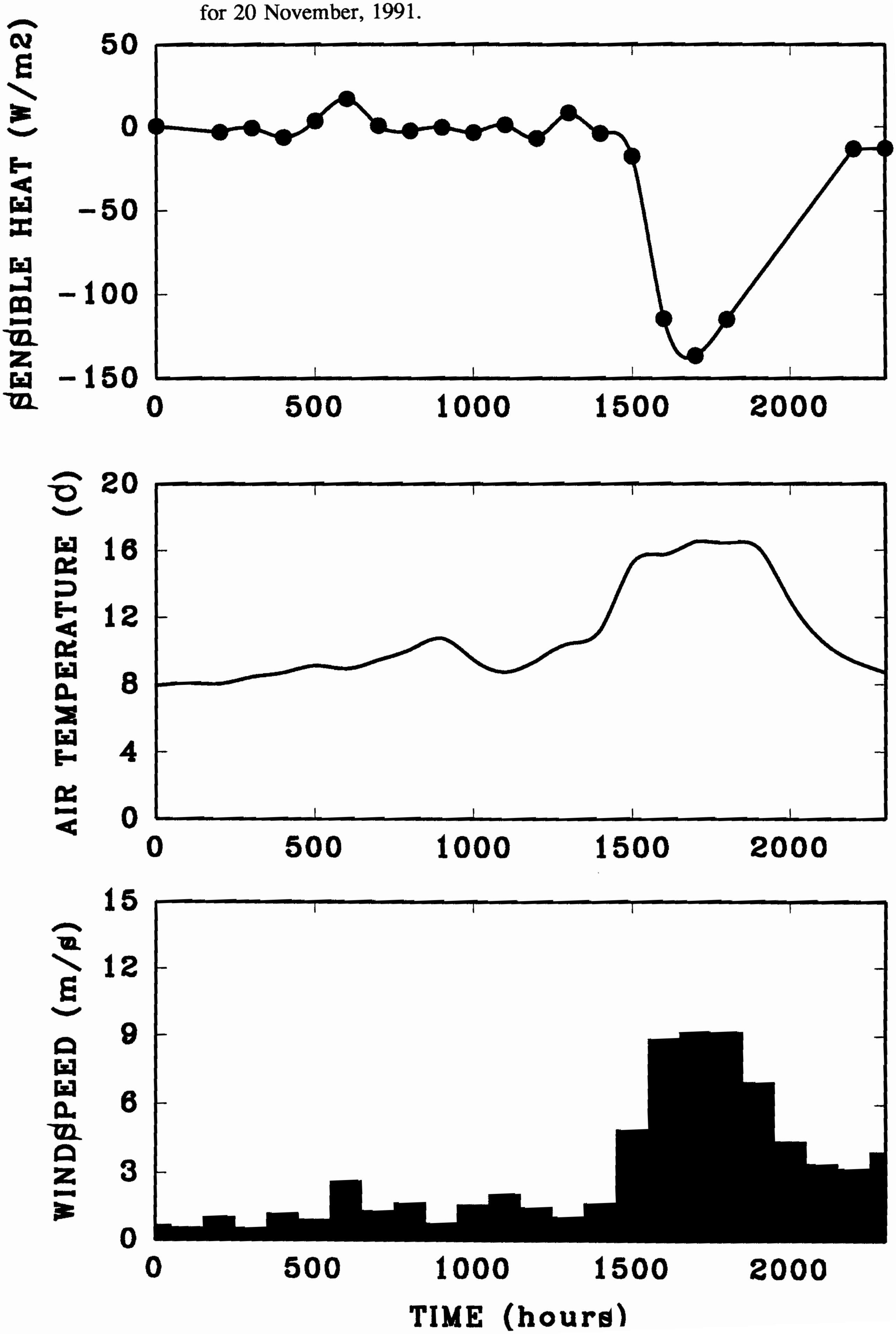


Figure 22: Plot of sensible heat flux, air temperature and horizontal windspeed for 20 November, 1991.



saw the movement of an occluded front over Montreal (this front being associated with a low pressure system passing to the south of Montreal). Although there was some precipitation (3.4 mm), and a relative humidity of 83 %, this day was characterized by predominantly sunny conditions. (It is worth noting that a day with a similar sensible heat flux pattern, 30 November 1991, was cloud covered.)

Despite the air temperatures of over 8°C in the early part of the day on 20 November 1991, there is virtually no heat exchange, with the exception of 0600 hours during which there was a slight increase in wind speed accompanied by some heat loss (close to 20 W m^{-2}). This may be a function of the low wind speeds and the fact that the air temperatures were steady over the previous 24 hours. In contrast, the sudden increase in wind speed to 9 m s^{-1}, and the accompanying increase in air temperature to over 16°C resulted in a large heat gain by the water body of up to approximately 140 W m^{-2}.

5.2.1.3 28 November 1992

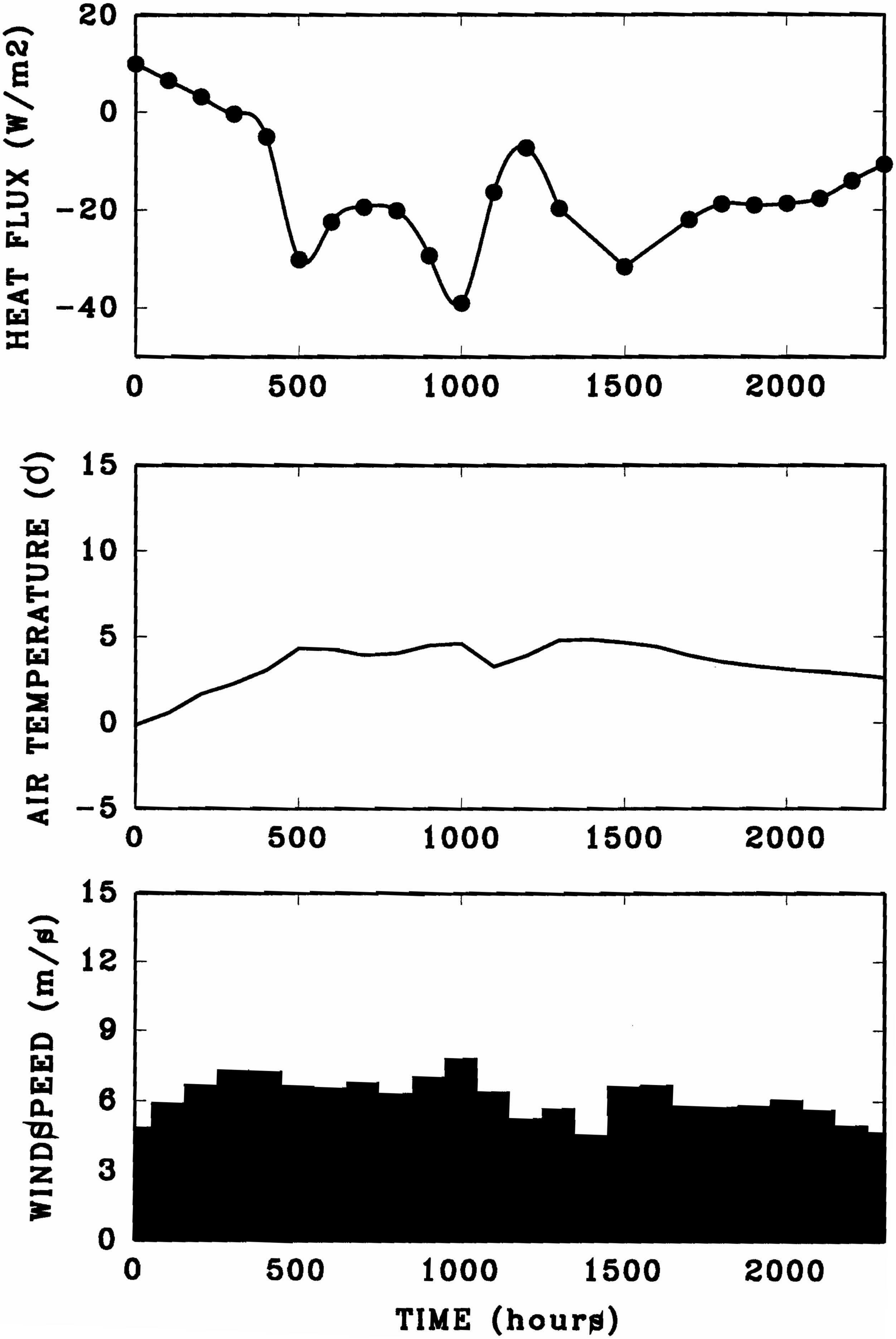
This day was selected for analysis because it was representative of more stationary meteorological conditions; air temperature varied only a few degrees Celsius and wind speeds were fairly constant (ie. there was no observed anomalous warm period as on the 20 and 30 November 1991, which produced dramatic responses in the sensible heat fluxes). The two days prior to 28 November 1991 had been slightly cooler with average air temperatures just below 0°C and moderate winds. Throughout the day, Montreal remained situated between a high pressure system to the south and a low pressure system to the northwest. Winds were quite strong throughout 28 November 1991 (greater than 6 m s^{-1}) and there was precipitation in the form of both rain and snow (0.8 mm and 1.6 cm respectively).

With air temperatures in the region of 1 and 2 °C there was some heat loss by the water; however, as air temperatures rose to above 2°C, the fluxes changed direction, and there was a net heat gain by the water body (Figure 23). Relatively strong winds (exceeding 7 m s^{-1}) did not appear to produce a correspondingly large increase in the magnitude of the sensible heat flux (as was the case on 20 November 1991).

5.2.1.4 3 December 1991

3 December 1991 is the only period in which a measurement of the sensible heat exchange by the water body was made during the final period of cooling before formation of the initial complete ice cover. 2 December 1991 marked a significant transition period in air temperature, as it dropped below 0°C and remained so for a relatively long period of time. The source area was not over the water body until late on 2 December 1991, and the measurement period lasted only about 9 hours as a period of rain and freezing rain commenced and the equipment failed. On 3 December 1991, Montreal was influenced by the passage of a low pressure system. This system resulted in overcast skies, and significant precipitation in the form of rain and snow (1.2 mm of rain and 18 cm of snow). The wind speeds remained relatively high throughout the day until about 1400 hours when freezing rain halted operation of the cup anemometer, making the recorded

Figure 23: Plot of sensible heat flux, air temperature and horizontal windspeed for 28 November, 1991.



wind speeds unreliable.

During the early morning of 3 December 1991 the air temperatures decreased slightly from just below -9°C to just below -10°C during which the fluxes ranged from about 80 to 120 W m^{-2}. This indicates a very substantial heat loss by the water body (Figure 24). Wind speeds were relatively high, ranging from 6 to 8 m s^{-1}.

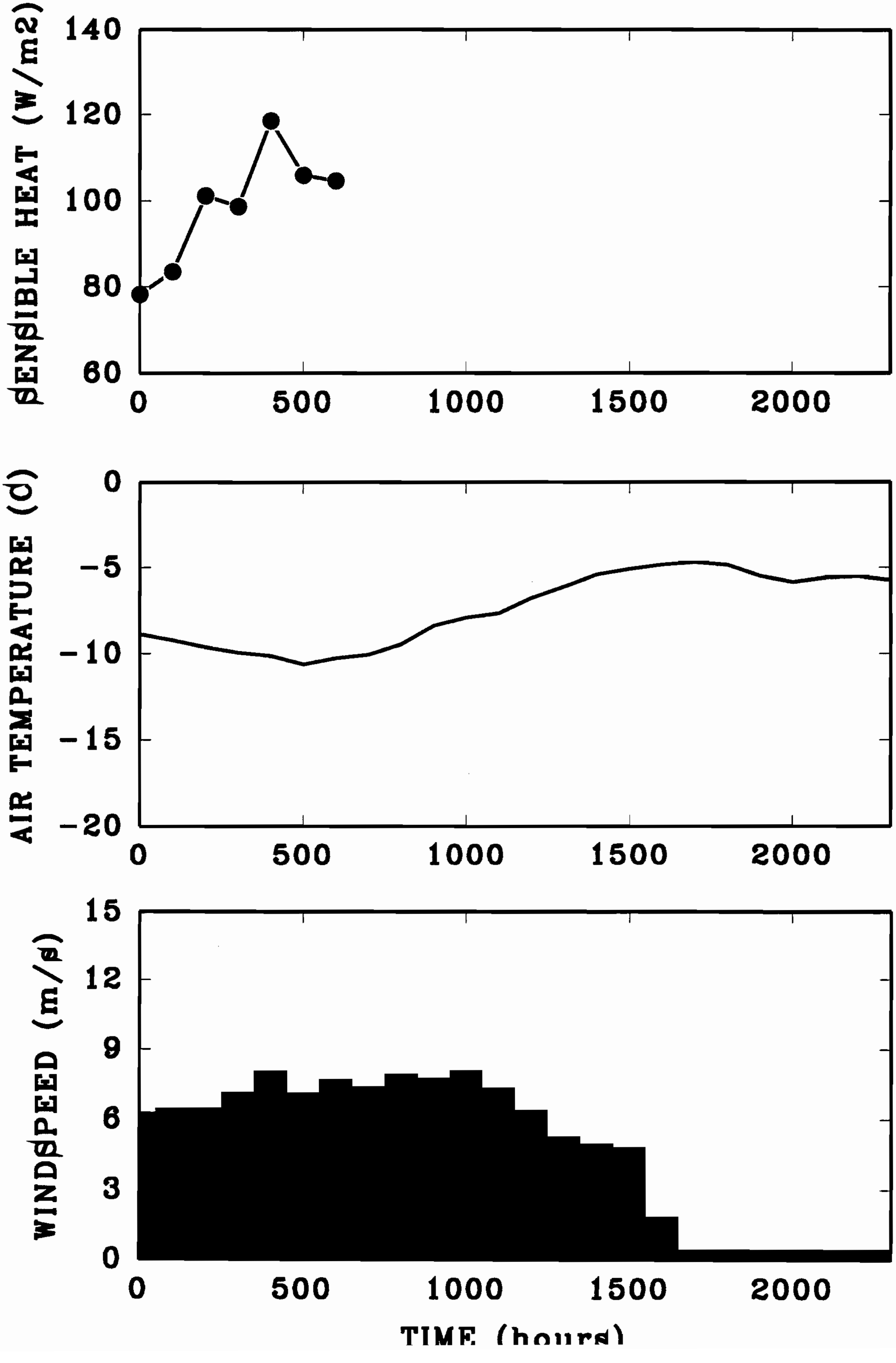
5.2.2 Complete Ice Cover - Cold Atmosphere

This period of complete ice coverage (6 December 1991 until approximately 9 December 1991) occurred shortly after the water body had gained a substantial amount of heat (30 November 1991) preceded by two days of very cold air temperatures. The air temperature decrease was rapid and continued until a complete ice cover had formed.

After the period of formation of the first complete ice cover over Lac St. Louis, there was only one short period during which the sensible heat flux was measured owing to continued breakage of the thermocouples. As it was impossible for safety reasons to travel between the shore and the breakwater on which the 4 m tower was located for a period of time after 3 December 1991, a Gill/thermocouple system (similar to that on the 4 m tower) was installed on the 17 meter tower onshore. This tower provided the majority of the sensible heat flux measurements for the remainder of the measurement period.

There was a five day period between which air temperatures dropped below 0°C

Figure 24: Plot of sensible heat flux, air temperature and horizontal windspeed for 3 December, 1991.



and the main lake basin (excluding the channel) completely froze over. The 4th and 5th of December 1991 were not completely ice covered; however on 6 December 1991 a complete ice cover had formed. It is speculated that the ice thickness, based on the 1974/75 measurements (Transport Canada, 1975), may have been on the order of 10-20 cm in depth. Measurements early on 7 December 1991 provided the only sensible heat flux measurements immediately after the initial ice cover formation (without snow cover).

5.2.2.1 7 December 1991

As stated above, measurements on this date provided the only recorded sensible heat flux measurements during the period of formation of the first ice cover. During the two days prior to 7 December 1991 the air temperatures were between 3 and 5°C lower than those on 7 December 1991, the relative humidity was lower on both days, and there was partial cloud cover.

During 7 December 1991, Montreal experienced the passage of a low pressure system and an accompanying warm front. Recorded winds over this measurement period were out of the southeast and wind speeds were as high as 7 m $s^{-1.}$ The air temperature varied little throughout the day (it averaged about -10°C). The relative humidity was 83 %, there was a complete cloud cover, and a snowstorm deposited 15.5 cm of snow. It is highly likely in this case, as in the case of 3 December 1991, that breakage of the thermocouples occurred with the onset of the precipitation event. The relatively low recorded sensible heat flux value at 0600 hours may be a result of either the drop in wind speed, or breakage of the thermocouple during that hour. The sensible heat flux on 7 December 1991, indicated losses of almost -45 W m^{-2} (Figure 25). In addition, it shows quite clearly that large quantities of heat are released during the formation of the ice cover.

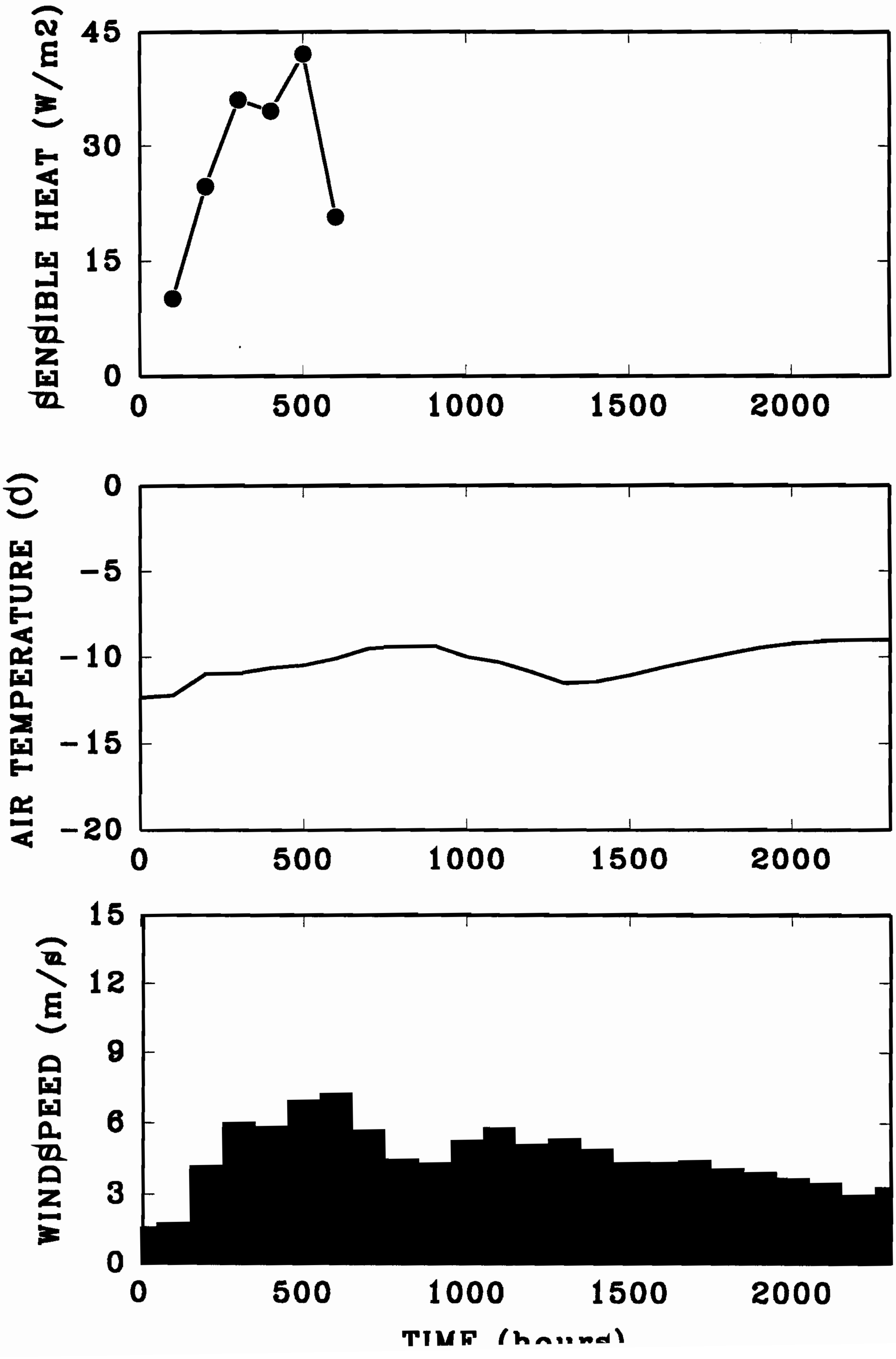
5.2.3 Partial Ice Cover - Warm Atmosphere

After the period of initial cooling and ice cover formation (approximately 2 to 9 December 1991), there were frequent periods of substantial melt which resulted in partial ice covers over Lac St. Louis. This partial ice coverage is typified by Figure 16 (in Chapter 4) which shows leads that generally open up just off the northern shore of the lake. In addition, the northwestern areas of the lake also tended to open up during these periods. The widths of these leads and open areas varied; however, their locations tended to change little throughout the 1991/92 winter. The source area estimates (Table 2 (b) and Figure 7 (c)) suggest that because measurements were made from the 17 m tower during this period, the source areas would generally include both open water and ice covered areas. It is difficult however, to determine the extent of the contributions of each.

5.2.3.1 11 December 1991

11 December 1991 was characterized by an extremely large negative heat flux

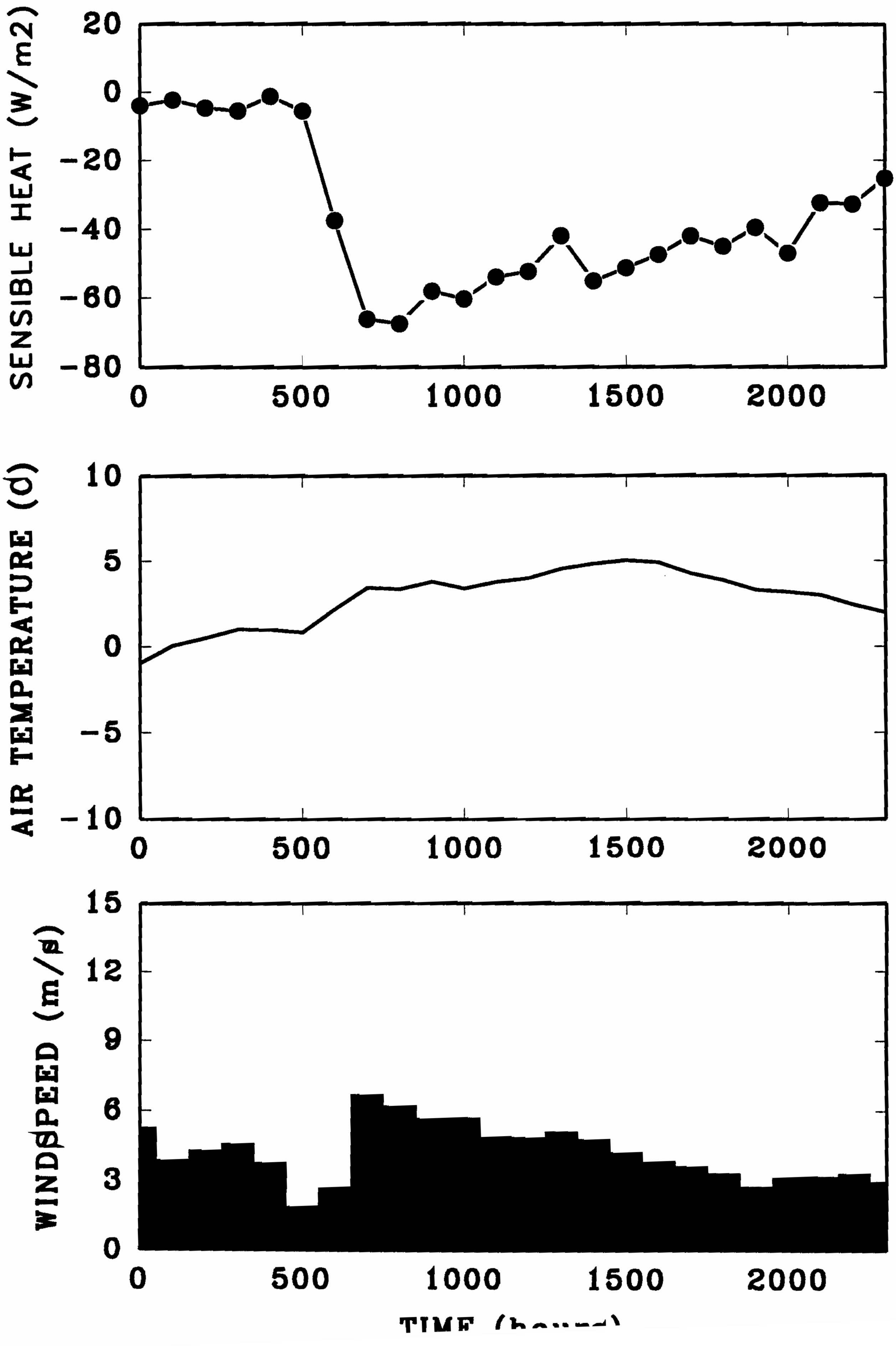
Figure 25: Plot of sensible heat flux, air temperature and horizontal windspeed for 7 December, 1991.



through the course of the day. 9 December 1991 was the first warm day after the initial period of ice cover formation, with an average air temperature of 2.1°C, and a 7.2 mm rainfall. The following day (10 December 1991) the air temperature dropped once again (to -4.8°C). The wind speeds were low on both days, and the cloud coverage partial. A site visit on 11 December 1991, indicated areas of open water near the shore on which the towers were located (similar to the ice cover extent in Figure 16).

11 December 1991 was a day on which there was a low pressure system centred the north of Montreal and a high pressure system to the south. This produced winds which brought with them warmer air (and an average air temperature for the day of 2.8°C). The winds were out of the east throughout the morning, switching to southeast in the afternoon. 11 December 1991 was a day of very substantial negative fluxes at the surface of Lac. St. Louis. In terms of total downwards flux over the day, it far exceeds most measured periods prior to the initial ice cover formation. Until approximately 0500 hours the air temperature was close to 0°C, and the fluxes were negative but close to 0 W m^{-2}. Not until the air temperature increased to over 2°C did the downwards heat flux become substantial (Figure 26). The heat flux of about -70 W m^{-2} was at 0800 hours when the air temperature was just over 3°C, and the wind speeds were 6 m s^{-1}. After that, the downward flux became smaller in magnitude (even with an increase in the air temperature to over 5°C), and the downwards heat flux gradually decreased throughout the day as the wind speed subsided.

Figure 26: Plot of sensible heat flux, air temperature and horizontal windspeed for 11 December, 1991.



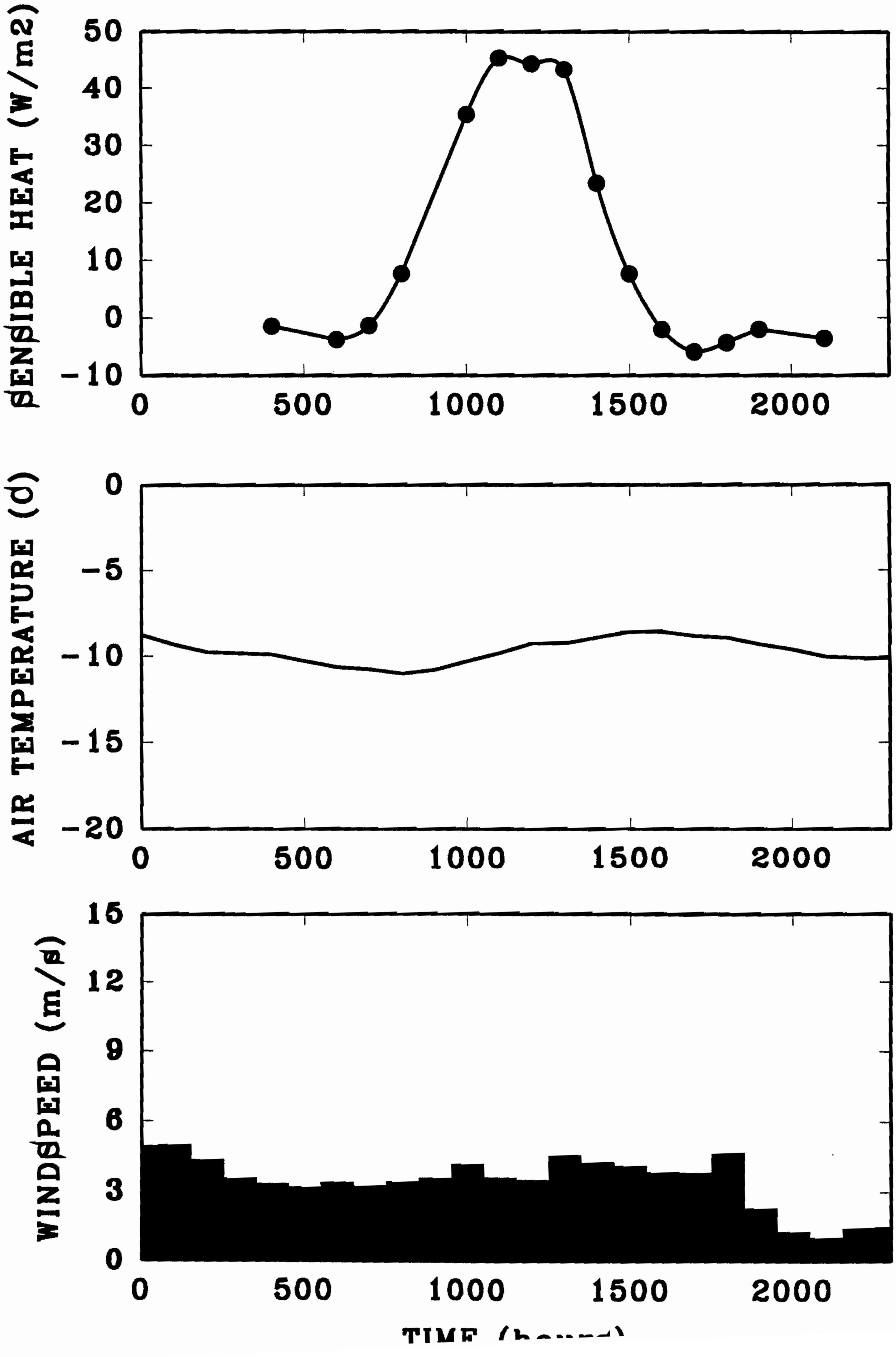
5.2.3.2 8 January 1992

Both 8 and 10 January 1992 (10 January 1992 is discussed in the next section) are days during and immediately following reformation of the complete ice cover after a warm period. 8 January 1992 was the first very cold day after a short period of warming (and after a large amount of precipitation in the form of rain). The ice coverage was partial over this period (with leads on the order of 20-40 m in width, again roughly similar to the ice coverage extents noted in Figure 16). The two previous days had been slightly windier and significantly warmer with air temperatures close to 0°C.

8 January 1992 was marked by a high pressure system centred just to the northwest of Montreal. As a result, the day was mainly cloud free, with little variation in the air temperature and wind speed evident through the day. The average air temperature was close to -10°C, and the wind speed between 3 and 4.5 m s^{-1} until about 1900 hours (when it decreased rapidly). The winds were out of the west and southwest throughout the measurement period.

With this decrease in air temperatures from 7 to 8 January 1992 there was a large heat loss by the lake (Figure 27). There was, on this date, a marked increase in the sensible heat flux which coincided with the early afternoon. At this point, the maximum heat flux was close to 45 W m^{-2}. This strong diurnal pattern did not appear to be a result of a change in the wind speed or air temperature, and it may in fact be a result of a change in the source area to predominantly over the lead, and/or a change in stability.

Figure 27: Plot of sensible heat flux, air temperature and horizontal windspeed for 8 January, 1992.



5.2.4 Ice and Snow Cover - Cold Atmosphere

Throughout the series of warm and cool periods in which the extent and makeup of the ice cover fluctuated extensively, there were periods with complete ice covers. There are two very different days in which the sensible heat fluxes over an ice and snow cover will be examined. The first, 10 January 1992, comes shortly after a period of warming and ice cover degradation. It is one of the first days in which the ice cover was essentially complete again, and there was a light cover of very fresh snow. The water body conditions are likely very similar to those proposed in section 5.2.2.

The second case is quite different. 12 February 1992 occurred during an extensive period of cold air temperatures. The ice probably exceeded 30-50 cm in depth at this time (an estimate based on information on Lac St. Louis data for the winter of 1974/75; Transport Canada, 1975), and the snow cover was deep and drifted.

5.2.4.1 10 January 1992

10 January 1992 provides an example of a day on which there was a fresh new snowcover over thin ice. On 10 January 1992, Montreal was between a low pressure system to the east and a high pressure system to the northwest. The relative humidity was 72 %, only 18 % of the sunlight hours were free of a cloud cover , the wind speeds were generally close to 3 m s^{-1}, and winds were out of the west and southwest. There had been a snowfall of close to 10 cm the previous day, with the light winds. The snowcover

appeared to be quite uniform.

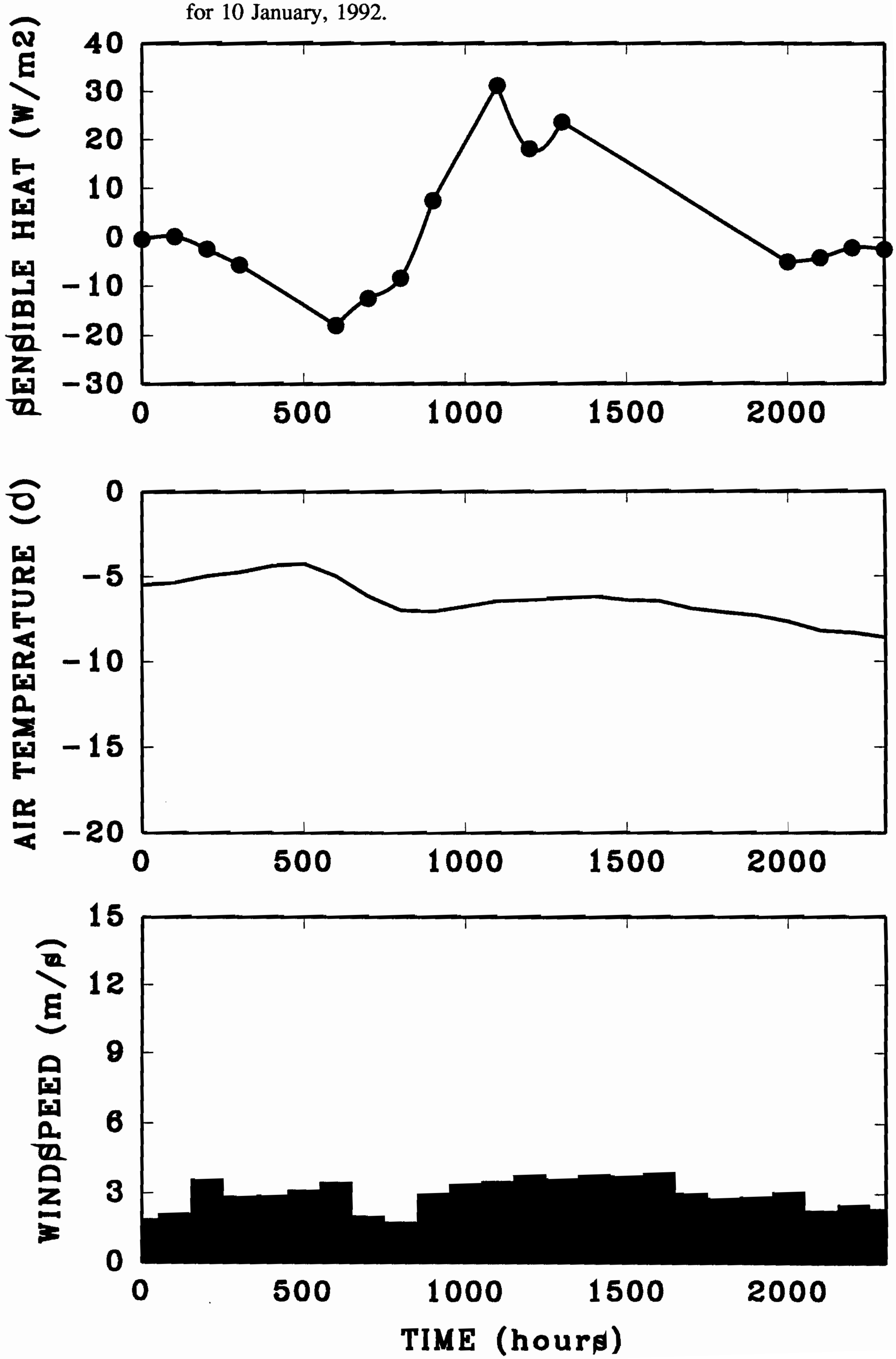
Initially the sensible heat flux was close to 0 W m^{-2}, but there were indications of a net heat input into the snow and ice over the period of a few hours which reversed close to 1000 hours (Figure 28). Air temperatures decreased after 0500 hours from just below -4°C to below -8°C at the end of the day. Some heat loss was noted in the early afternoon (of just over 30 W m^{-2}), with a decrease in sensible heat flux to close to 0 W m^{-2}, again late in the day. Wind speeds were at a maximum during the period of greatest heat flux.

5.2.4.2 12 February 1992

12 February 1992 was chosen as a case study to illustrate the dampened and varied fluxes under a certain type of surface condition. It follows an extensive stretch of cold weather, in which the ice cover was very solid (as indicated previously, on the order of 30-50 cm), and the snow pack deep, drifted, and compact (with conditions similar to those in Figure 18). It follows a day (11 February 1992) of similar conditions; however, 12 February 1992 experienced slightly warmer air temperatures (an average air temperature for the day of -8.6°C). A high pressure system centred just to the southwest of Montreal on 12 February 1992 brought mainly sunny conditions, a low relative humidity (of 52 %), a low average air temperature of -21.4°C, and wind speeds just over 3 m s^{-1}. Winds were generally out of the west and southwest.

The sensible heat flux was only available after 0400 hours on 12 February 1992

Figure 28: Plot of sensible heat flux, air temperature and horizontal windspeed for 10 January, 1992.



due to a shift in wind direction (Figure 29). There is no strong pattern with respect to the sensible heat flux directions, as the fluxes remained small and varied throughout the day. The most notable period of the day occurred between 1700 and 1800 hours when the fluxes were approximately -19 W m^{-2}, an occurrence marked by an increase in the air temperature by 7°C to -18°C, as well as an increase in wind speed.

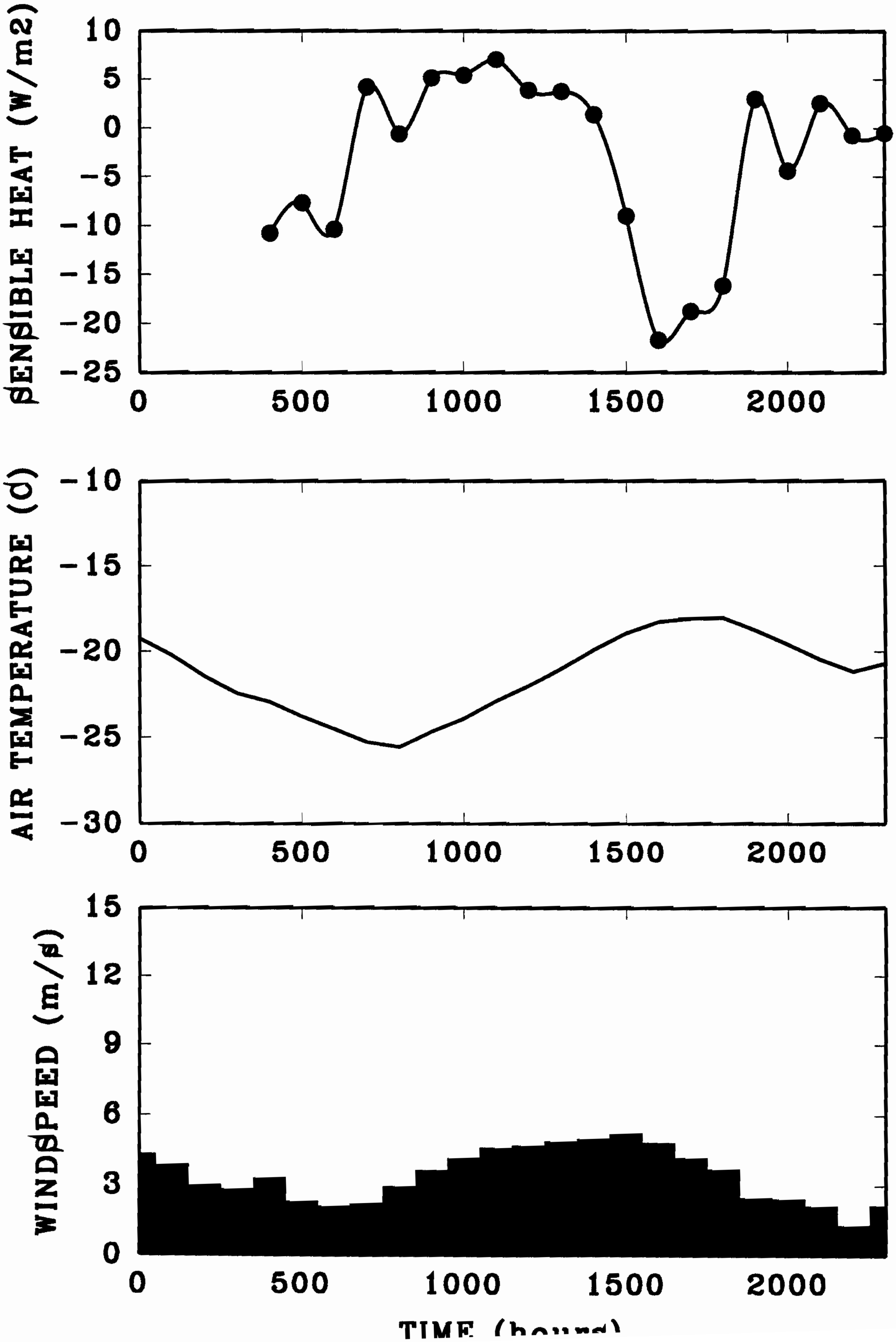
5.2.5 Discussion of Case Studies

This section will present a more speculative discussion of the aforementioned sets of case studies. It will focus on the implications of the sensible heat fluxes in terms of heat exchanges (between the atmosphere and water body), and how the characteristics of the water body may influence these exchanges. This discussion will be broken down (as in the previous section) according to the various waterbody and meteorological conditions (open water, ice cover, partial ice cover, and snow and ice cover).

5.2.5.1 Open Water

This period includes the case studies up to and including 3 December 1991. Although water temperatures were not measured in Lac St. Louis, some estimates of water temperatures can be made from the sensible heat flux information in specific cases. As discussed in Chapter 2, there are two factors that would suggest a rapid response of water temperatures to air temperature over Lac St. Louis; 1) the lake is well mixed, and

Figure 29: Plot of sensible heat flux, air temperature and horizontal windspeed for 12 February, 1992.



2) the water body is quite shallow. Therefore, it is quite plausible that the water temperature gradient is small (ie. water temperatures are likely close to being uniform through the depth of the water body) and close to 0°C before freeze-up.

On 15 Nov 1991, the fact that early in the day the sensible heat flux was close to 0 W m^{-2} and there was negligible response to an increase in wind speed (of over 5 m s^{-1}) suggests that the water temperatures and air temperatures were very similar during the early part of this day (ie. the water temperature was in the vicinity of 3-5°C). Not until the air temperature rose later in the day to between 7 and 10 °C, did the sensible heat flux appear to respond to a similar increase in wind speed (again of over 5 m s^{-1}).

The low wind speeds on 20 November 1991 (and the previous day) may have resulted in reduced mixing at the water surface. This may have produced a period of warming of the water surface only. Hence the upper layer of the water would respond to the air temperature very quickly, and with less turbulent waters, the transfer of heat downwards would be considerably slower. The large afternoon heat gain recorded on 20 November 1991, although obviously a function of the increased air temperature, may also have been related to the increased mixing of the water with the extremely strong winds making the water more turbulent and hence mixing more rapid.

The rise in air temperature on 28 November 1991 to over 2°C (which produced a change in direction of the recorded sensible heat flux to positive), indicates that the water temperatures may have been close to 2°C. Again, as on 15 November 1991, a relatively strong increase in wind speed did not produce a correspondingly large increase in the sensible heat flux. This may have been a result of air temperatures exceeding the water temperatures by only a few degrees Celsius (ie. the average air temperature for that day was slightly greater than 3°C).

5.2.5.2 Ice Cover

This period includes only the case study of 7 December 1991. For this period of complete thin ice coverage over Lac St. Louis, water temperatures may again be inferred from the flux and air temperature measurements. As has been suggested previously, due to the shallow depth and relatively rapid mixing in Lac St. Louis, water temperatures are likely quite uniform throughout the depth of the lake and not much greater than 0°C just prior to ice cover formation. Within this context, however, it is anticipated that with the significant heat gain just prior to cooling and the rapid ice cover formation, one might expect that a more significant amount of heat would be retained by the water body after the final period of cooling than had the final period of cooling been less rapid and longer (ie. there may not have been enough time to allow for complete mixing of the water body through its entire depth). Nonetheless, it is expected that due to the shallow nature of the lake, the water temperature was fairly uniform through its depth.

The formation of a complete ice cover would decrease turbulent mixing of the water by wind stress. This would probably be a period of time during which heat transfer from the sediments to the overlying water would be a factor in increasing water temperatures (although somewhat less than immediately before ice cover formation when the less turbulent waters would result in a less rapid removal of heat near the lake bottom). Therefore, it may have made a slight contribution to heat loss through the ice to the atmosphere.

5.2.5.3 Partial Ice Cover

This period includes the case studies of 11 December 1991 and 8 January 1992. With the return to a partial ice coverage, the opportunity arose to investigate on a number of occasions, the extent to which the water body gained heat (ie. due to the periods of substantial air temperature increase). With the opening of leads, there would be an increase in the magnitude of fluxes over these areas (due to the removal of the ice cover which acts to dampen these fluxes). This time of periodic melting and reforming of the ice cover also greatly changed the structure of the ice cover. Whereas it had initially formed rapidly into smooth black ice, the periods of melt combined with various forms of precipitation, created a snow-ice mixture that was spatially very non-homogeneous. This implies a reduced efficiency in heat transfer through the ice cover (Rossinskii, 1979; Adams, 1981).

On both 11 December 1991 and 8 January 1992 it is unknown whether the majority of the fluxes were from over the open water or the ice. It is anticipated on both days that over the open water the heat contributed to increasing water temperatures, whereas over the ice it contributed to melting of the ice surface.

5.2.5.4 Ice and Snow Cover

This period includes the case studies of 10 January 1992 and 12 February 1992. On 10 January 1992 it is not expected that the water and atmosphere would be decoupled since the ice and snow cover was relatively thin. However, under the conditions of 12 February 1992, the water body would be expected to be completely decoupled from the atmosphere. Should there still be much heat stored in the sediments, it would most likely contribute to heating of the water below the ice. However, given that this body of water has a significant throughflow, this heat may be removed within a relatively short period of time.

5.2.6 Case Study Comparisons

Meteorological conditions over the winter of 1991/92 were quite variable, thereby permitting observation of the rate and degree to which Lac St. Louis responds to meteorological changes, particularly in air temperature. It appears to be very clear that the response of a shallow body of open water is very rapid; when a shift to a lower air temperature occurs, heat is lost rapidly by the water body, and the heat flux diminishes very quickly (essentially reaching a new equilibrium), until another shift in air temperature occurs. The reverse also appears true.

The air temperatures and nature of an ice cover appear to be of primary importance with respect to controlling the sensible heat fluxes over Lac St. Louis.

Obviously, there is a strong dampening of the sensible heat flux with the presence of an ice cover. A relationship between wind speed and heat fluxes is also apparent in the 1991/92 data whereby an increase in the horizontal wind speed increases the frictional drag, and hence the vertical wind speed and the magnitude of the sensible heat flux.

For example, on 15 November 1991, a day with relatively small fluxes, the air temperature remained close to 5°C for a large part of the day, with an increase later in the day to close to 10°C. Of interest on this day are the two peaks in the horizontal wind speed; the first before the rise in air temperature, and the second accompanying the rise in air temperature. No significant heat flux was noted until the second peak in the horizontal wind speed, indicating the importance of the vertical temperature gradient in determining the sensible heat flux.

Generally the magnitude of the fluxes is larger over open water than when an ice cover is present. For example, sensible heat fluxes of well over 100 W m^{-2} in magnitude were noted on a number of occasions when no ice cover was present, whereas with the presence of a complete ice cover, the recorded sensible heat flux never exceeded 45 W m^{-2}.

The cases examined prior to ice cover formation show changes in sensible heat fluxes on the order of 30 to 40 W m^{-2} with moderate winds and shifts in the air temperatures of just a few degrees Celsius (15 and 28 November 1992), while with large air temperature shifts (on the order of 8°C plus) over the period of a few hours (accompanied by very strong winds), the recorded sensible heat fluxes can exceed 100 W m^{-2} (as shown on 20 and 30 November 1991, and 3 December 1991). The only recorded period of extensive heat loss by the water body was on 3 December 1991 just prior to the formation of the initial ice cover, when sensible heat fluxes reached 120 W m^{-2}. Other periods in the fall in which the sensible heat fluxes were positive were generally encountered when the winds were blowing from northerly directions (ie. overland source area).

3 December 1991 and 7 December 1991 provide contrasts of the ice free and ice covered water body. With the onset of negative air temperatures (3 December 1991), the water heat loss was on the order of 120 W m^{-2}, whereas 7 December 1991, a day with similar air temperatures and the first day with a complete ice cover and no snow cover produced sensible heat fluxes of close to 45 W m^{-2}. These days are comparable as the air temperatures were similar, both sets of heat flux measurements were taken before sunrise and the horizontal wind speeds were similar. Thus with the formation of the thin ice cover (approximately 10-20 cm), the heat flux was dampened to approximately 1/3 of the open water values.

Another pair of days worth examining are 8 and 10 January 1992. They followed a short period of warming in which there had been a net downwards flux. 8 January 1992 showed heat losses over a partial ice cover (although some uncertainty exists regarding the exact 'source' on this day, whether it be open water, ice, or both) with recorded sensible heat flux losses of up to 45 W m^{-2}. Two days following this, on 10 January 1992, a day in which wind speeds were slightly lower and the air temperatures slightly higher (than on 8 January 1992), the recorded sensible heat flux losses were as high as 30 W m^{-2}; this with a complete ice cover overlain by a thin layer of new snow (deposited on 9 January 1992). These two cases lends support again to the suggestion that the surface responses (whether they be associated with increasing or decreasing the temperature of the open water, increasing the surface ice thickness, or melting surface snow and ice) are very rapid, as the magnitude of the sensible heat fluxes over this period were not much lower in magnitude than those observed during the formation of the initial ice cover. This suggests that the response of the water body is extremely rapid, if a short warming period can result in a subsequent period of heat release similar in magnitude to that experienced with the initial freeze-up.

Later in the season, when the ice cover had been established for a long period of time and there was a deep snowpack, it appears highly likely that there existed virtually no heat exchange between the water and the overlying atmosphere. As well, with the numerous periods of rain and thaw, the ice cover was likely made up of snow-ice and hence was less conductive (than for example black ice) (Rossinskii, 1979; Adams, 1981). Arctic modelling of ice thicknesses and heat exchanges (Maykut, 1978) suggests that with ice thicknesses up to 1 m there is still a significant surface heat exchange occurring. However, once these depths are exceeded, very little exchange occurs. Two factors contribute to the significant heat exchanges in the presence of such thick ice in the Arctic; 1) water temperatures are higher below the ice than in a shallow water body, and 2) air temperatures are generally very low in the Arctic. Together, these factors produce a larger gradient and hence greater surface exchanges for a given ice thickness (although it is recognized that the freezing point of saltwater and freshwater and the composition of freshwater and saltwater ice are not identical). Under conditions such as those experienced in the vicinity of Lac St. Louis over the 1991/92 winter, and due to the nature of the water body, the air/water temperature gradients will tend to be less, due to the fact that air temperatures are not as low as those experienced in the Arctic and water temperatures will be closer to 0°C. Therefore, the water body and the overlying atmosphere should become decoupled over Lac St. Louis with a smaller ice thickness than in Arctic environments.

In summary, sensible heat fluxes over the measurement period proved to be extremely varied, and the responses to shifts in the short term air temperature record very swift. Examination of a number of individual daily periods indicates that heat exchanges over the water body are very rapid (ie. heat is readily received and given up). Comparison of the magnitude of the heat fluxes obtained over Lac St. Louis in the 1991/92 winter with those obtained in Antarctica by Allison et al. (1982) indicate magnitudes that are not entirely dissimilar. In the Antarctic, Allison et al. (1982) recorded daily fluxes one month prior to ice cover formation on the order of several 100 W m^{-2}, with those following the initial ice cover formation on the order of 40 W m^{-2} (with ice less than 0.2 m thick). Just prior to and just following the formation of the initial ice cover, maximum sensible heat fluxes of approximately 120 W m^{-2} and 45 W m^{-2} were recorded at Lac St. Louis (with estimated ice thicknesses also less than 0.2 m). However, in this environment, fluxes of this magnitude are extremely shortlived.

CHAPTER 6

CONCLUSIONS

As outlined in Chapter 1, this thesis has two major objectives. The primary objective is to investigate the effect of meteorological conditions and ice coverage on the magnitude and direction of sensible heat fluxes over Lac St. Louis. Secondly, it is an evaluation of a Gill/thermocouple eddy correlation system in this type of environment. The results of this study are discussed in Chapters four and five. An examination of the general meteorological conditions including the air temperature, wind speeds and directions, and precipitation, and the effect of these conditions on the ice and snow cover is made in Chapter four, along with a discussion of the performance of the instrumentation. Chapter five examined the sensible heat flux record and specific cases throughout the measurement period representative of various meteorological or source area conditions.

6.1 Instrumentation

One of the objectives of this study was to examine the use of an eddy correlation system, a Gill propeller anemometer in conjunction with a fast response thermocouple, as a means of conducting heat flux measurements at remote sites under winter conditions.

Although there were some minor problems with the Gill propellers, the majority of the problems were associated with the thermocouples. The 25 μm wire with an unshielded junction cannot withstand strong winds and heavy precipitation events, a significant problem as the periods through which these events occur are often the most interesting in terms of the sensible heat fluxes. Furthermore, the chromel-constantan wire connecting the thermocouple to the datalogger often snapped under cold conditions, producing unreliable and intermittent heat flux measurements. This problem might be solved by further insulating the wire, however, there is no clear means of preventing breakage of the fine wire thermocouple other than to monitor it very closely under harsh conditions or use another form of temperature sensor. Despite the problems induced by marked temperature fluctuations, the system produced credible results for a significant proportion of the winter. This suggests that the system has considerable potential in case studies where its performance can be monitored more frequently. With respect to stability corrections for the system, it is recommended that the Gill/thermocouple system be run together with a sonic anemometer under the various conditions experienced throughout the study (in order that sensible heat flux measurements and corrections can be validated). Placement of the system high above the measurement surface (particularly during the periods in which the fluxes are small), to minimize losses in instrument sensitivity is also recommended.

6.2 Sensible Heat Fluxes and General Meteorological Conditions over Lac St. Louis

The 1991/92 winter proved to be a challenging period in which to study the sensible heat fluxes over Lac St. Louis. Consequently, the analysis was constrained by: 1) a sensible heat record which was not continuous, both because there were continual equipment breakdowns and continual shifts in the source area, 2) the continual shifting and changing of the numerous variables which influence the sensible heat fluxes and which made it difficult to separate the influences of specific variables from each other, 3) continual and rapid changes in the source area, as a measurement surface, often creating a patchy surface, and making it difficult to know whether the majority of the fluxes were from over the water or the ice, 4) winds which were often stronger from the measurement directions and generally were also associated with warmer air temperatures, and 5) a lack of stability information after 3 December 1991 which increased the errors associated with the sensible heat flux measurements after this date.

However, there are a number of important conclusions which can be drawn from the sensible heat fluxes and related variables obtained over this 1991/92 winter season:

1) The general meteorological conditions indicated that there were an unusually large number of warm periods throughout the measurement period, a factor which is evident in the extremely large standard deviation of the mean daily air temperature for December and January, (close to triple the normal). The wind speeds and directions were

as expected, with predominant directions of west and southwest. However, significant and frequent shifts in wind direction meant that the source area for the towers was over the lake only intermittently.

2) The ice cover was extremely variable as it appears that variables other than just the air temperature contribute to its formation and extent. Over Lac St. Louis, the wind speeds, wind directions, and water velocities probably all play an important role; the winds by controlling to some degree the extent and position of the ice cover, and the water velocity as it likely results in a more rapid and extensive mixing of the water body (which makes the heat loss by the water extremely rapid).

3) It is quite evident that the response of the water body to the weather conditions (and particularly to changes in air temperature) was very rapid. This is likely a result of the shallow nature of the lake as well as the rapid rate of mixing of the water. Thus unlike deep lakes and oceans there is no heat source from which to continually draw heat to the water surface. It is quite likely therefore, that the water temperature drops rapidly through the entire depth of the lake and remains close to 0°C during the period of ice cover formation.

4) Corrected sensible heat fluxes over Lac St. Louis yielded the following: sensible heat fluxes into the water body of over 140 W m^{-2} during warm events in the early part of the measurement period, a heat loss of up to 120 W m^{-2} with the onset of

cooling, followed by a drop in the maximum recorded heat loss to close to 45 W m^{-2} with the formation of a complete snowfree ice cover. Sensible heat fluxes of close to 30 W m^{-2} were recorded with a complete ice cover and a thin snow cover (again following a period of warming). The sensible heat flux record suggests that heat gains and losses occur quickly over this type of water body, after which it quickly reaches a steady state and the sensible heat fluxes become more or less negligible. These maximum sensible heat flux values measured over Lac St. Louis through the 1991/92 winter were comparable to heat fluxes obtained in studies conducted over Antarctica (Allison et al., 1982), the difference being that in the Antarctic study, unlike the present study, the fluxes were maintained over an extended period of time.

Therefore, it is evident from this study, that shallow temperate water bodies may have implications in terms of localized moderating effects in the short term due to the rapid uptake or release of heat in response to changes in air temperatures. However, the magnitudes are largely a function of the short term air temperature patterns, and further research of this sort at a single site over an extended period of time (numerous winter seasons) would give a better indication of whether the heat fluxes under the conditions noted are generally reproduced from season to season.

6.3 Recommendations for Future Research

There are a number of recommendations which can be made for further research relating not only to the method of instrumentation, but also to the measurement of sensible heat fluxes over temperate fresh water surfaces, and in particular, to the fresh water surface over which this particular study was conducted, Lac St. Louis:

1) In terms of the instrumentation system, it is recommended that the measurement height be relatively high, the Gill/thermocouple system tested in conjunction with a sonic anemometer at the field site and under the field conditions, the wires connecting the thermocouples to the datalogger insulated, and the diameter of the thermocouple wire increased (enough so as to keep errors to a minimum and to minimize breakage).

2) With respect to Lac St. Louis, an attempt should be made to ensure that a complete set of sensible heat fluxes can be obtained (which would require the use of an instrument system better able to be left for long periods of time unattended, and an additional measurement site on the opposite side of the lake). As well, close monitoring of the water currents and velocities, and ice thicknesses, spatial coverage, and variability would provide a great deal of information useful in the interpretation of the sensible heat flux information. Use of a ground probing radar might help provide information relating to thicknesses and spatial variability of the lake ice. Monitoring of the variability in water temperatures not only with depth, but spatially, would also provide valuable

information on ice cover formation, and heat release from bottom sediments.

3) Finally, it is suggested that a study of this nature conducted over a water body with less throughflow might provide conditions more suited to a detailed study of water temperature and ice cover conditions in conjunction with the sensible heat flux information. These types of conditions might provide information which may be more easily generalized for other areas of Canada. In this context, it would be interesting to observe the heat exchanges over water bodies with various heat storage capacities (ie. lakes of various depths and spatial extents), in conjunction with other relevant information, with the objective of attempting to model lake ice formation.

References

Adams, W. P. (1981), Snow and Ice on Lakes, In:Handbook of Snow, Principles, Processes, Management and Use, D. M. Gray and D. H. Male (Ed), ©1981 Pergamon Press, Canada Ltd. p 437-474.

Allison, I., C. M. Tivendale, G. J. Tivendale, G. J. Akerman, J. M. Tahn and R. H. Willis, (1982). Seasonal variations in the surface energy exchanges over Antarctic sea ice and coastal waters. Annals of Glaciology, Vol. 3 p 12-16.

Allison, I. A. (1973). Energy Fluxes over Polar Surfaces. World Meteorological Society, No. 361 p 116-132.

Allison, I. A. and G. Akerman, (1980). Sea Ice and Ocean Energy Balance Studies at Mawson, Antarctica. In: Sea Ice Processes and Models; Proceedings of the Arctic Ice Dynamics Joint Experiment International Commission on Snow and Ice Symposium, Ed. by R. S. Pritchard, University of Washington Press, Seattle and London, ©1980.

Amiro, B. D., J. M. Laporte and G. A. Thorne (1988). Evapotranspiration and Surface Water Balance Measurements at the Whiteshell Research Area, 1985 to 1987. Atomic Energy of Canada Limited, p 1-7.

Amiro, B. D. and E. E. Wuschke (1987). Evapotranspiration from a Boreal Forest Drainage Basin using an Energy Balance/Eddy Correlation Technique. Boundary-Layer Meteorology, Vol. 38, p 125-139.

Amiro, B. D. and P. A. Davis (1988). Statistics of Atmospheric Turbulence Within a Natural Black Spruce Forest Canopy. Boundary-Layer Meteorology, Vol. 44, p 267-283.

Andreas, E. L., C. A. Paulson, R. M. Williams, R. W. Lindsay, and J. A. Businger (1979). The turbulent heat flux from Arctic leads. Boundary Layer Meteorology, Vol. 17, p 57-91.

Andreas, E. L. (1980). Estimation of Heat and Mass Fluxes over Arctic Leads. Monthly Weather Review, Vol. 108, p 2057-2063.

Andreas, E. L. (1982). Sensible and Latent heat fluxes and humidity profiles following a step change in surface moisture. U. S. Army Corps of Engineers, CRREL Report, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, p 82-120.

Ashton, G. P. (Ed), Thermal Regime of Lakes and Rivers, In: River and Lake Ice Engineering, Water Resources Publication, ©1986, p 203-260.

Bello, R. and J. D. Smith (1990). The Effect of Weather Variability on the Energy Balance of a Lake in the Hudson Bay Lowlands, Canada. Arctic and Alpine Research, Vol. 22, p 98-107.

Bengtsson, L. (1981). Experiences on the Winter Thermal Regime of Rivers and Lakes with Emphasis on Scandanavian Conditions. Proceedings: International Symposium on Ice, Quebec, p 11-54.

Bilello, M. A. (1968), Water Temperatures in a Shallow Lake During Ice Formation, Growth, and Decay. Water Resources Research, Vol. 4, p 749-760.

Breon, F. M., R. Frouin and C. Gautier (1990). Satellite Estimates of Downwelling Longwave Irradiance at the Surface During FIFE. Symposium on FIFE, American Meteorological Society, p 92-97.

Businger, J. A., T.C. Wyngaard, Y. Izumi and E. F. Bradly (1971). Flux Profile Relationships in the Atmospheric Surface Layer. Journal of Atmospheric Science, Vol. 28, p 181-189.

Canadian Climate Normals, Volume 2, Temperature, 1951-1980. Environment Canada, 1982.

Canadian Climate Normals, Volume 5, Wind, 1951-1980. Environment Canada, 1982.

Canadian Climate Normals, Temperature and Precipitation, Quebec, 1951-1980. Environment Canada, 1982.

Deptuch-Stapf, A. (1992). El Nino - Southern Oscillation (ENSO) Update. Climatic Perspectives, Environment Canada, Vol. 14, p 7.

Deriugin, A. G. (1972), Snow Ice and its Significance in Computing the Thickness of the Ice Cover. CRREL Draft Translation 299, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Dyer, A. J. and B. B. Hicks (1970). Flux-Gradient Relationships in the Constant Flux Layer. Quarterly Journal of the Royal Meteorological Society, Vol. 96, p 715-721.

Erisman, J. and J. Duyzer (1991). A Micrometeorological Investigation of Surface Exchange Parameters over Heathland. Boundary-Layer Meteorology, Vol. 57, p 115-128.

Fitzgarrald, D. R. and K. E. Moore (1990). Turbulent transports over tundra. JGR-Atmospheres Able-3a Special Volume.

Fritschen, L. J. and L. W. Gay Environmental Instrumentation, Springer-Verlag, New York, N.Y., ©1979, 216 p.

Gosink, J. P. (1987), Northern Lake and Reservoir Modeling. Cold Regions Science and Technology, Vol. 13, p 281-300.

Gow, A. J. and J. W. Govoni (1982). Ice Growth on Post Pond, 1973-1982. CRREL Report 83-4, U.S. Army Cold Regions Research and Engineering Lab, Hanover, New Hampshire, p 1-25.

Granger, R. J. and D. H. Male (1978). Melting of a Prairie Snowpack. Journal of Applied Meteorology, Vol. 17, p 1833-1842.

Hicks, B. B. (1972). Propeller Anemometers as Sensors of Atmospheric Turbulence. Boundary Layer Meteorology, Vol. 3, p 214-228.

Horst, T. W. (1973). Corrections for Response Errors in a Three-Component Propeller Anemometer. Journal of Applied Meteorology, Vol. 12, p 716-725.

Kondo, J., O. Kanechika and N. Yasuda (1978). Heat and Momentum Transfers under Strong Stability in the Atmospheric Surface Layer. Journal of the Atmospheric Sciences, Vol. 35, p 1012-1021.

Leclerc, M. D. Ghouri, J. Robert, and J. Tessier (1987), Modelisation des ecoulements de l'archipel de montreal par elements finis: aspects divers de l'application. Revue Internationale des sciences de l'eau, Vol. 3, p 41-56.

Lloyd, C. R., A. D. Culf, A. J. Dolman and J. H. C. Gash (1991). Estimates of Sensible Heat Flux from Observations of Temperature Fluctuations. Boundary-Layer Meteorology, Vol. 57, p 311-322.

Male, D. H. and R. J. Granger (1981). Snow surface energy exchange. Water Resources Research Vol. 17, p 609-627.

Marsh, P. and T. D. Prowse (1987). Water Temperature and Heat Flux at the Base of River Ice Covers. Cold Regions Science and Technology, Vol. 14, p 33-50.

Maykut, G. A. (1978). Energy exchange over young sea ice in the Central Arctic. Journal of Geophysical Research Vol. 83, p 3646-3658.

Maykut, G. A. (1986). The surface heat and mass balance. In:The Geophysics of Sea Ice Ed. by Norbert Untersteiner, ©1986 Plenum Press, N. Y. p 395-463.

McBean, G. A. (1972). Instrument Requirements for Eddy Correlation Measurements. Journal of Applied Meteorology, Vol. 11, p 1078-1085.

McBean, G. The Atmospheric Boundary Layer. In: The Geophysics of Sea Ice. Ed. by Norbert Untersteiner, ©1986 Plenum Press, N. Y., p 283-337.

McMillen, R. T. (1988). An Eddy Correlation Technique with Extended Applicability to Non-Simple Terrain. BoundaryLayer Meteorology, Vol. 43, p 231-245.

Michel, B. (1971), Winter Regime of Rivers amd Lakes, CRREL, U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Milne, R., J. D. Deans, E. D. Ford, P. G. Jarvis, J. Leverenz, and D. Whitehead, (1985). A Comparison of Two Methods of Estimating Transpiration Rates form a Sitka Spruce Plantation. Boundary-Layer Meteorology, Vol. 32, p 155-175.

Miyake, M., R. W. Stewart and R. W. Burling (1970). Spectra and Cospectra of Turbulence over Water. Quarterly Journal of the Royal Meteorological Society, Vol. 96, p 138-143.

National Oceanic and Atmospheric Administration (NOAA). National Meteorological Center Meteorological Operations Division and Climate Analysis Center, Daily Weather Maps, Weekly series, ©1991, Washington, D.C..

National Oceanic and Atmospheric Administration (NOAA). National Meteorological Center Meteorological Operations Division and Climate Analysis Center, Daily Weather Maps, Weekly series, ©1992, Washington, D.C..

O'Neill, K. and G. D. Ashton (1981), Bottom Heat Transfer to Water Bodies in winter, CRREL Special Report 81-18, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Oke, T. R. Boundary Layer Climates (Ed. 2), Methuen & Co., Great Britain, ©1987, 435 p.

Panofsky, H. A. and J. A. Dutton . Atmospheric Turbulence: models and methods for engineering applications, John Wiley and Sons, New York, ©1984, 397 p.

Rossinskii, K. I. (1979), The Thermal Regime of Reservoirs, Draft Translation 700. CRREL, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Rouse, W. R., S. Hardill and A. Silis (1989). Energy Balance of the Intertidal Zone of Western Hudson Bay II: Ice-Dominated Periods and Seasonal Patterns. Atmoshere-Ocean, Vol. 27, p 346-366.

Sadhuram, Y., P. Vethamony, A. Suryanargyana, G. N. Swamy and J. S. Sastry (1988). Heat Energy Exchange over a Large Water Body Under Stable Atmospheric Conditions. Boundary Layer Meteorology, Vol. 44, p 171-180.

Said, F. and A. Druilhet (1991). Experimental Study of the Atmospheric Marine Boundary Layer from In-Situ Aircraft Measurements (Toscane-T Campaign): Variability of Boundary Conditions and Eddy Flux Parameterization. Boundary-Layer Meteorology, Vol. 57, p 219-249.

Schmid, H. P., H. A. Cleugh, C. S. B. Grimmond and T. R. Oke (1991). Spatial Variability of Energy Fluxes in Suburban Terrain. Boundary-Layer Meteorology, Vol. 58, p 249-276.

Schmid, H. P. and T. R. Oke (1990). A Model to Estimate the Source Area Contributing to Turbulent Exchange in the Surface Layer over Patchy Terrain. Quarterly Journal of the Royal Meteorological Society, Vol. 116, p 965-988.

Sellers, P. J., F. G. Hall, D. E. Strebel, E. T. Kanemasu, R. D. Kelly, B. L. Blad, B. J. Markham, and J. R. Wang (1990). Experimant Design and Operations. Symposium on FIFE, American Meteorological Society, p 1-5.

Shuttleworth, W. J. (1988). Corrections for the Effect of Background Concentration Change and Sensor Drift in RealTime Eddy Correlation Systems. Boundary-Layer Meteorology, Vol. 42, p 167-180.

Spittlehouse, D. L. and T. A. Black (1979). Determination of Forest Evapotranspiration Using Bowen Ratio and Eddy Correlation Measurements. Journal of Applied Meteorology, Vol. 18, p 647-653.

Stigebrandt, A. (1987). Dynamics of an Ice Covered Lake with Throughflow. Nordic Hydrology, Vol. 9, p 219-244.

Stull, R. B. An Introduction to Boundary Layer Meteorological, Klewer Academic Publishers, Dordrecht, The Netherlands, ©1988.

Swinback, W. C. (1968). A Comparison between Predictions of Dimensional Analysis for the Constant-Flux Layer and Observations in Unstable Conditions. Quarterly Journal of the Royal Meteorological Society, Vol. 94, p 460-467.

The Climate of Montreal, Climatological Studies Number 39, The Climate if Canadian Cities Number 4. Minister of Supply and Services, Canada, ©1987.

Thorpe, M. R., E. G. Banke and S. D. Smith (1973). Eddy Correlation Measurements of Evaporation and Sensible Heat Flux over Arctic Sea Ice. Journal of Geophysical Research, Vol. 78, p 3573-3584.

Transport Canada (1975), Services graphiques d'epaisseurs de glace et de neige Lac St. Louis (nord), Hiver 1974-75. Transport Canada, Services Maritimes-District de Montreal.

Tvede, A. M. (1978), The Heat Storage of Lake Mjosa, Norway: Interactions Between Ice Cover, Climate and the Energy Exchange Processes. IAHR Symposium on Ice Problems, Lulea Sweden, p 103-115.

Watte, C., and C. Marsh (1978), Statistical Analysis and Prediction Methods for Ice Cover Formation and Growth on Saguenay River (Canada). IAHR Symposium on Ice Problems, Lulea Sweden, p 117-129.

Weaver, H. L. (1990). Temperature and Humidity FluxVariance Relations Determined by One-Dimensional Eddy Correlation. Boundary-Layer Meteorology, Vol. 53, p 77-91.

Wettlaufer, J. S. , R. Colony and N. Untersteiner (1990). Measurement of the Thermal Regime in Perennial Sea Ice. Annals of Glaciology, Vol. 14, p 1282-1286.

APPENDIX 1 A

```
Program:  QH.DOC   Program for 3-axis Gill and 2 FRT's
Flag Usage:
Input Channel Usage:
Excitation Channel Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:


*      1        Table 1 Programs
  01: .09375    Sec. Execution Interval

01:  P10        Battery Voltage
  01: 25        Loc : Battery Voltage

02:  P2         Volt (DIFF) (25 um Fast Response Thermocouples (FRT))
  01: 2         Reps
  02: 12        7.5 mV fast Range
  03: 1         IN Chan
  04: 1         Loc : LOC 1-FRT#1 and LOC 2-FRT#2
  05: 16.95     Mult
  06: 0         Offset

03:  P2         Volt (DIFF) (Vertical Windspeed, w)
  01: 1         Rep
  02: 15        2500 mV fast Range
  03: 3         IN Chan
  04: 3         Loc : Vertical Windspeed
  05: .01764    Mult (Calibration Coefficient for Gill)
  06: 0         Offset

04:  P2         Volt (DIFF) (Horizontal Windspeed, u)
  01: 1         Rep
  02: 15        2500 mV fast Range
  03: 4         IN Chan
  04: 10        Loc : Horizontal Windspeed (u)
  05: .01764    Mult
  06: 0         Offset

05:  P2         Volt (DIFF) (Horizontal Windspeed, v)
  01: 1         Rep
  02: 15        2500 mV fast Range
  03: 5         IN Chan
  04: 5         Loc : Horizontal Windspeed (v)
  05: .01764    Mult
  06: 0         Offset

06:  P30        Z=F
  01: 2         F
  02: 0         Exponent of 10
  03: 6         Z Loc : (constant=2)

07:  P47        Z=X^Y
  01: 10        X Loc (u)
  02: 6         Y Loc (2)
  03: 7         Z Loc : (u**2)
```

```
08:  P47        Z=X^Y
  01: 5         X Loc (v)
  02: 6         Y Loc (2)
  03: 8         Z Loc : (v**2)

09:  P33        Z=X+Y
  01: 7         X Loc (u**2)
  02: 8         Y Loc (v**2)
  03: 9         Z Loc : (u**2 + v**2)

10:  P39        Z=SQRT(X) (SQRT (u**2 + v**2))
  01: 9         X Loc (u**2 +v**2)
  02: 4         Z Loc : Single Horizontal Windspeed value, U

11:  P58        Low Pass Filter (FRT#1, FRT#2, w, U)
  01: 4         Reps
  02: 1         Sample Loc
  03: 11        Loc : FRT#1, FRT#2, w, U
  04: .00055    Weighting Factor

12:  P35        Z=X-Y
  01: 3         X Loc
  02: 13        Y Loc
  03: 15        Z Loc : (w'= w - Low Pass Filtered w)

13:  P35        Z=X-Y
  01: 1         X Loc (25 um FRT#1)
  02: 11        Y Loc (Low Pass Filter FRT#1)
  03: 16        Z Loc : (t1' = FRT#1 - Low Pass Filtered FRT#1)

14:  P35        Z=X-Y
  01: 2         X Loc (25 um FRT#2)
  02: 12        Y Loc (Low Pass Filter FRT#2)
  03: 17        Z Loc : (t2' = FRT#2 - Low Pass Filtered FRT#2)

15:  P36        Z=X*Y
  01: 16        X Loc (t1')
  02: 15        Y Loc (w')
  03: 18        Z Loc : (t1'*w')

16:  P37        Z=X*F
  01: 18        X Loc (t1'*w')
  02: 1200      F
  03: 20        Z Loc : (SENSIBLE HEAT FLUX #1 - QH1)

17:  P36        Z=X*Y
  01: 17        X Loc (t2')
  02: 15        Y Loc (w')
  03: 19        Z Loc : (t2'*w')

18:  P37        Z=X*F
  01: 19        X Loc (t2'*w')
  02: 1200      F
  03: 21        Z Loc : (SENSIBLE HEAT FLUX #2 - QH2)
```

```
19:  P35       Z=X-Y
  01: 4        X Loc (U)
  02: 14       Y Loc (Low Pass Filter U)
  03: 22       Z Loc : (U'= U - Low Pass Filtered U)

20:  P36       Z=X*Y
  01: 22       X Loc (U')
  02: 15       Y Loc (w')
  03: 23       Z Loc : (w'*U')

21:  P92       If time is
  01: 0        minutes into a
  02: 60       minute interval
  03: 10       Set high Flag 0 (output)

22:  P77       Real Time
  01: 110      Day,Hour-Minute

23:  P78       Resolution
  01: 1        High Resolution

24:  P71       Average
  01: 4        Reps
  02: 18       Loc QH1, QH2, t1'*w', t2'*w'

25:  P71       Average
  01: 1        Rep
  02: 23       Loc (w'*U')

26:  P71       Average
  01: 1        Rep
  02: 3        Loc Average Vertical Windspeed, w

27:  P82       Standard Deviation
  01: 1        Rep
  02: 3        Sample Loc Standard Deviation Vertical Windspeed, w

28:  P         End Table 1


*     2        Table 2 Programs
  01: 0.0000   Sec. Execution Interval

01:  P         End Table 2


*     3        Table 3 Subroutines

01:  P         End Table 3


*     A        Mode 10 Memory Allocation
  01: 28       Input Locations
  02: 64       Intermediate Locations
  03: 0.0000   Final Storage Area 2
```

*	C	Mode 12 Security
01:	0000	LOCK 1
02:	0000	LOCK 2
03:	0000	LOCK 3

 Input Location Assignments (with comments):

Key:
T=Table Number
E=Entry Number
L=Location Number

T:	E:	L:	
1:	2:	1:	Loc : LOC 1-FRT#1 and LOC 2-FRT#2
1:	3:	3:	Loc : Vertical Windspeed
1:	10:	4:	Z Loc : Single Horizontal Windspeed value, U
1:	5:	5:	Loc : Horizontal Windspeed (v)
1:	6:	6:	Z Loc : (constant=2)
1:	7:	7:	Z Loc : (u**2)
1:	8:	8:	Z Loc : (v**2)
1:	9:	9:	Z Loc : (u**2 + v**2)
1:	4:	10:	Loc : Horizontal Windspeed (u)
1:	11:	11:	Loc : FRT#1, FRT#2, w, U
1:	12:	15:	Z Loc : (w'= w - Low Pass Filtered w)
1:	13:	16:	Z Loc : (t1' = FRT#1 - Low Pass Filtered FRT#1)
1:	14:	17:	Z Loc : (t2' = FRT#2 - Low Pass Filtered FRT#2)
1:	15:	18:	Z Loc : (t1'*w')
1:	17:	19:	Z Loc : (t2'*w')
1:	16:	20:	Z Loc : (SENSIBLE HEAT FLUX #1 - QH1)
1:	18:	21:	Z Loc : (SENSIBLE HEAT FLUX #2 - QH2)
1:	19:	22:	Z Loc : (U'= U - Low Pass Filtered U)
1:	20:	23:	Z Loc : (w'*U')
1:	1:	25:	Loc : Battery Voltage

APPENDIX 1 B

```
Program:TOWER.DOC  Program for 1-axis Gill & 2 FRT's
Flag Usage:
Input Channel Usage:
Excitation Channel Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:


*       1          Table 1 Programs
  01: .09375       Sec. Execution Interval

01:   P10          Battery Voltage
  01: 25           Loc : Battery Voltage

02:   P2           Volt (DIFF) (25 um Fast Response Thermocouples (FRT))
  01: 2            Reps
  02: 12           7.5 mV fast Range
  03: 1            IN Chan
  04: 1            Loc : LOC 1-FRT#1 and LOC 2-FRT#2
  05: 16.95        Mult
  06: 0            Offset

03:   P2           Volt (DIFF) (Vertical Windspeed)
  01: 1            Rep
  02: 15           2500 mV fast Range
  03: 3            IN Chan
  04: 3            Loc : Vertical Windspeed
  05: .01764       Mult
  06: 0            Offset

04:   P58          Low Pass Filter (Wind Speed and FRT's)
  01: 3            Reps
  02: 1            Sample Loc
  03: 4            Loc :
  04: .00055       Weighting Factor

05:   P35          Z=X-Y
  01: 3            X Loc
  02: 6            Y Loc
  03: 9            Z Loc : (w'= w - Low Pass Filtered Windspeed)

06:   P35          Z=X-Y
  01: 1            X Loc
  02: 4            Y Loc
  03: 7            Z Loc : (t1'=FRT#1 - Low Pass Filtered t1)

07:   P35          Z=X-Y
  01: 2            X Loc
  02: 5            Y Loc
  03: 8            Z Loc : (t2' = FRT#2 - Low Pass Filtered t2)

08:   P36          Z=X*Y
  01: 7            X Loc
  02: 9            Y Loc
  03: 10           Z Loc : (t1'* w')
```

```
09:  P37        Z=X*F
  01:  10       X Loc
  02:  1200     F
  03:  12       Z Loc : (Sensible Heat Flux #1, QH1)

10:  P36        Z=X*Y
  01:  8        X Loc
  02:  9        Y Loc
  03:  11       Z Loc : (t2' * w')

11:  P37        Z=X*F
  01:  11       X Loc
  02:  1200     F
  03:  13       Z Loc : (Sensible Heat Flux #2, QH2)

12:  P92        If time is
  01:  0        minutes into a
  02:  60       minute interval
  03:  10       Set high Flag 0 (output)

13:  P77        Real Time
  01:  110      Day,Hour-Minute

14:  P78        Resolution
  01:  1        High Resolution

15:  P71        Average
  01:  4        Reps
  02:  10       Loc (QH1, QH2, t1'*w', t2'*w')

16:  P71        Average
  01:  1        Rep
  02:  3        Loc (Average Vertical Windspeed, w)

17:  P82        Standard Deviation
  01:  1        Rep
  02:  3        Sample Loc (Standard Deviation of Vertical Windspeed)

18:  P          End Table 1


*      2        Table 2 Programs
  01: 0.0000    Sec. Execution Interval

01:  P          End Table 2


*      3        Table 3 Subroutines
```

```
01:  P         End Table 3

*       A         Mode 10 Memory Allocation
   01: 28         Input Locations
   02: 64         Intermediate Locations
   03: 0.0000     Final Storage Area 2
```

```
Page 3   Mode C
```

```
*       C         Mode 12 Security
   01: 0000       LOCK 1
   02: 0000       LOCK 2
   03: 0000       LOCK 3
```

Page 4   Input Location Assignments (with comments):

Key:
T=Table Number
E=Entry Number
L=Location Number

```
T:  E:  L:
1:  2:  1:  Loc : LOC 1-FRT#1 and LOC 2-FRT#2
1:  3:  3:  Loc : Vertical Windspeed
1:  4:  4:  Loc :
1:  6:  7:  Z Loc : (t1'=FRT#1 - Low Pass Filtered t1)
1:  7:  8:  Z Loc : (t2' = FRT#2 - Low Pass Filtered t2)
1:  5:  9:  Z Loc : (w'= w - Low Pass Filtered Windspeed)
1:  8: 10:  Z Loc : (t1'* w')
1: 10: 11:  Z Loc : (t2' * w')
1:  9: 12:  Z Loc : (Sensible Heat Flux #1, QH1)
1: 11: 13:  Z Loc : (Sensible Heat Flux #2, QH2)
1:  1: 25:  Loc : Battery Voltage
```

APPENDIX 2 A

```
$nofloatcalls
$debug
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c       PROGRAM TO CALCULATE ATMOSPHERIC STABILITY
c
c       Input is as an ascii file. It calculates the Monin-Obukhov
c       Length  and the stability z/L for two sets of w't' data.
c       It is set up to read missing values as -99999 or 99999.
c       Missing values are output as -999 or 999.
c
c       The file variables will            The output variables will
c       be read in this order:             be as follows:
c
c       d (Julian Day)                     d (Julian Day)
c       t (time)                           t (time)
c       w (w't'1)                          w (w't'1)
c       s (w't'2)                          s (w't'2)
c       v (Qh1)                            u (u'w')
c       x (Qh2)                            c (air temperature)
c       u (u'w')                           y (wind speed)
c       o (AVG w)                          r (wind direction)
c       q (STD w)                          a1 (Monin-Obukhov Length 1)
c       c (air temperature)                a2 (Monin-Obukhov Length 2)
c       y (wind speed)                     b1 (stability, z/L 1)
c       r (wind direction)                 b2 (stability, z/L 2)
c                                          o (AVG w)
c                                          q (STD w)
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

        program stabil2
        dimension d(600),t(600),c(600),w(600),u(600),s(600)
       dimension o(600),q(600),y(600),r(600)
       dimension a1(600),b1(600),a2(600),b2(600),p(600)
        write(*,*)'what is the tower height, z ?'
        read(*,*)z
        do 1 i=1,600
     read(3,*,end=2)d(i),t(i),w(i),s(i),v,x,u(i),o(i),q(i),
    ^c(i),y(i),r(i)
1       continue
2       nmax=i-1
c       start calculating for qh1
        do 31 j=1,nmax
        if(w(j).eq.0.0)a1(j)=999
        if(w(j).eq.0.0)b1(j)=0.0
        if(w(j).eq.0.0)goto 31
```

```
      if(w(j).eq.-99999)a1(j)=-999
      if(w(j).eq.99999)a1(j)=-999
      if(w(j).eq.-99999)b1(j)=-999
      if(w(j).eq.99999)b1(j)=-999
      if(w(j).eq.-99999)goto 31
      if(w(j).eq.99999)goto 31
      p=abs(u(j))
      a1(j)=-((((p(j))**0.5)**3.0)*(c(j)+273.0)/(9.8*0.4*w(j)))
      b1(j)=z/a1(j)
31    continue
c     calculate for qh2
      do 48 j=1,nmax
      if(s(j).eq.0.0)a2(j)=999
      if(s(j).eq.0.0)b2(j)=0.0
      if(s(j).eq.0.0)goto 48
      if(s(j).eq.-99999)a2(j)=-999
      if(s(j).eq.99999)a2(j)=-999
      if(s(j).eq.-99999)b2(j)=-999
      if(s(j).eq.99999)b2(j)=-999
      if(s(j).eq.-99999)goto 48
      if(s(j).eq.99999)goto 48
      p=abs(u(j))
      a2(j)=-((((p(j))**0.5)**3.0)*(c(j)+273.0)/(9.8*0.4*s(j)))
      b2(j)=z/a2(j)
48    continue
      do 50 j=1,nmax
      write(*,*)d(j),t(j),'running',b1(j),b2(j),c(j)
     write(4,100)d(j),t(j),w(j),s(j),u(j),c(j),y(j),r(j),
     *a1(j),a2(j),b1(j),b2(j),o(j),q(j)
50    continue
100   format(f5.1,1x,f6.1,1x,f12.5,1x,f12.5,1x,f12.5,1x,f10.2,1x,
     *f10.2,1x,f10.2,1x,f10.2,1x,f10.2,1x,f12.5,1x,f14.5,1x,f10.5,
     *1x,f10.5)
      stop
      end
```

APPENDIX 2 B

```
$nofloatcalls
$debug
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c       PROGRAM TO CALCULATE SENSIBLE HEAT FLUX AS A FUNCTION
c       OF THE AIR TEMPERTURE FROM  w't'
c
c       Input is an ascii file.  It calculates new Qh values for two
c       sets of w't' data. Missing values are read as -99999 or 99999
c       and output as -999 and 999.  The input is the output from the
c       program that calculates stability (STABIL2.FOR).
c
c       The input variables will        The output variables will
c       be as follows:                          be as follows:
c
c       d (Julian Day)                  d (Julian Day)
c       t (time)                        t (time)
c       w (w't'1)                       w (w't'1)
c       s (w't'2)                       s (w't'2)
c       u (u'w')                        u (u'w')
c       c (air temperature)             qh1 (new Qh1)
c       y (wind speed)                  qh2 (new Qh1)
c       r (wind direction)              c (air temperature)
c       a1 (L1)                         y (wind speed)
c       a2 (L2)                         r (wind direction)
c       b1 (z/L1)                       a1 (L1)
c       b2 (z/L2)                       a2 (L2)
c       o (AVG w)                       b1 (z/L1)
c       q (STD w)                       b2 (z/L2)
c                                       o (AVG w)
c                                       q (STD w)
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
        program qhcalc1
        dimension d(600),t(600),w(600),s(600),u(600),c(600)
        dimension y(600),r(600),a1(600),a2(600),b1(600),b2(600)
        dimension qh1(600),qh2(600),o(600),q(600)
        do 1 i=1,600
     read(3,*,end=2)d(i),t(i),w(i),s(i),u(i),c(i),y(i),r(i),a1(i),
    *a2(i),b1(i),b2(i),o(i),q(i)
c      write(*,*)d(i),t(i),w(i),s(i),u(i),c(i),y(i),r(i),a1(i),
c     *a2(i),b1(i),b2(i),o(i),q(i)
1       continue
2       nmax=i-1
c       start calculating for qh1
c       for Ta >22.5
        do 3 j=1,nmax
```

```
      if (w(j).eq.99999)qh1(j)=-999
      if (w(j).eq.99999)goto 3
      if (c(j).gt.22.5)qh1(j)=1010.0*1.168*w(j)
      if (c(j).le.22.5) goto 3
3     continue
c     for Ta>17.5
      do 9 j=1,nmax
      if (w(j).eq.99999)qh1(j)=-999
      if (w(j).eq.99999)goto 9
      if (c(j).gt.17.5.and.c(j).le.22.5)qh1(j)=1010.0*1.188*w(j)
      if (c(j).le.17.5) goto 9
9     continue
c     for Ta>12.5
      do 10 j=1,nmax
      if (w(j).eq.99999)qh1(j)=-999
      if (w(j).eq.99999)goto 10
      if (c(j).gt.12.5.and.c(j).le.17.5)qh1(j)=1010.0*1.209*w(j)
      if (c(j).le.12.5) goto 10
10    continue
c     for Ta>7.5
      do 11 j=1,nmax
      if (w(j).eq.99999)qh1(j)=-999
      if (w(j).eq.99999)goto 11
      if (c(j).gt.7.5.and.c(j).le.12.5)qh1(j)=1010.0*1.230*w(j)
      if (c(j).le.7.5) goto 11
11    continue
c     tor Ta>2.5
      do 12 j=1,nmax
      if (w(j).eq.99999)qh1(j)=-999
      if (w(j).eq.99999)goto 12
      if (c(j).gt.2.5.and.c(j).le.7.5)qh1(j)=1010.0*1.252*w(j)
      if (c(j).le.2.5) goto 12
12    continue
c     for Ta>-2.5
      do 13 j=1,nmax
      if (w(j).eq.99999)qh1(j)=-999
      if (w(j).eq.99999)goto 13
      if (c(j).gt.-2.5.and.c(j).le.2.5)qh1(j)=1010.0*1.275*w(j)
      if (c(j).le.-2.5) goto 13
13    continue
c     for Ta>-7.5
      do 14 j=1,nmax
      if (w(j).eq.99999)qh1(j)=-999
      if (w(j).eq.99999)goto 14
      if (c(j).gt.-7.5.and.c(j).le.-2.5)qh1(j)=1010.0*1.299*w(j)
      if (c(j).le.-7.5) goto 14
```

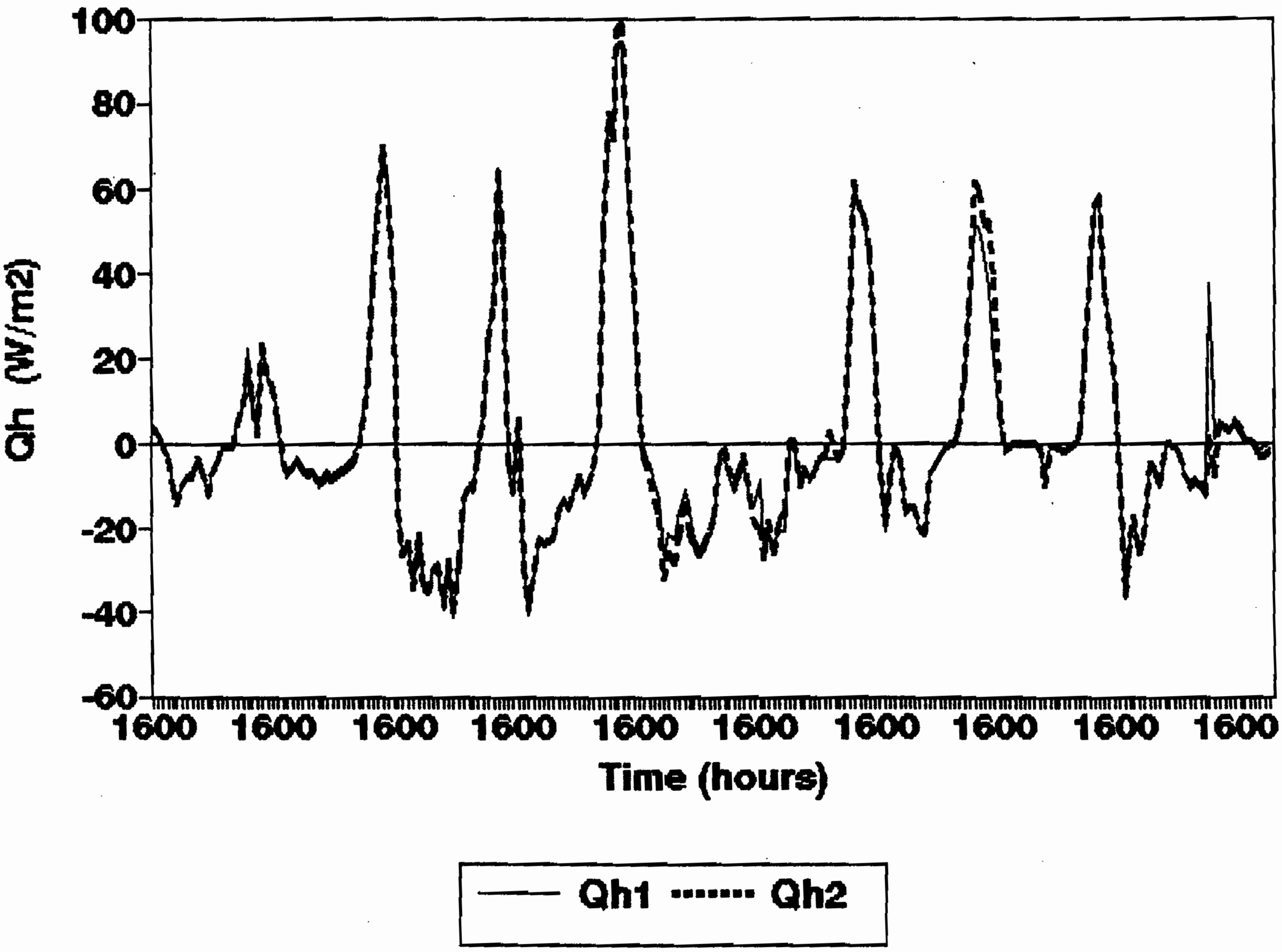
```
14      continue
c       for Ta>-12.5
        do 15 j=1,nmax
        if (w(j).eq.99999)qh1(j)=-999
        if (w(j).eq.99999)goto 15
        if (c(j).gt.-12.5.and.c(j).le.-7.5)qh1(j)=1010.0*1.324*w(j)
        if (c(j).le.-12.5) goto 15
15      continue
c       for Ta>-17.5
        do 16 j=1,nmax
        if (w(j).eq.99999)qh1(j)=-999
        if (w(j).eq.99999)goto 16
        if (c(j).gt.-17.5.and.c(j).le.-12.5)qh1(j)=1010.0*1.349*w(j)
        if (c(j).le.-17.5) goto 16
16      continue
c       for Ta>-22.5
        do 17 j=1,nmax
        if (w(j).eq.99999)qh1(j)=-999
        if (w(j).eq.99999)goto 17
        if (c(j).gt.-22.5.and.c(j).le.-17.5)qh1(j)=1010.0*1.376*w(j)
        if (c(j).le.-22.5) goto 17
17      continue
c       for Ta>-27.5
        do 18 j=1,nmax
        if (w(j).eq.99999)qh1(j)=-999
        if (w(j).eq.99999)goto 18
        if (c(j).gt.-27.5.and.c(j).le.-22.5)qh1(j)=1010.0*1.404*w(j)
        if (c(j).le.-27.5) goto 18
18      continue
c       for Ta<-27.5
        do 19 j=1,nmax
        if (c(j).le.-27.5)qh1(j)=1010.0*1.433*w(j)
        if (w(j).eq.-99999)qh1(j)=-999
        if (w(j).eq.-99999)qh1(j)=-999
19      continue
c       start calculating for qh2
c       for Ta>22.5
        do 103 j=1,nmax
        if(s(j).eq.99999)qh2(j)=-999
        if(s(j).eq.99999)goto 103
        if(c(j).gt.22.5)qh2(j)=1010.0*1.168*s(j)
        if(c(j).le.22.5)goto 103
103     continue
c       for Ta>17.5
        do 109 j=1,nmax
        if(s(j).eq.99999)qh2(j)=-999
```

```
      if(s(j).eq.99999)goto 109
      if(c(j).gt.17.5.and.c(j).le.22.5) qh2(j)=1010.0*1.188*s(j)
      if(c(j).le.17.5)goto 109
109   continue
c     for Ta>12.5
      do 110 j=1,nmax
      if(s(j).eq.99999)qh2(j)=-999
      if(s(j).eq.99999)goto 110
      if(c(j).gt.12.5.and.c(j).le.17.5) qh2(j)=1010.0*1.209*s(j)
      if(c(j).le.12.5)goto 110
110   continue
c     for Ta>7.5
      do 111 j=1,nmax
      if(s(j).eq.99999)qh2(j)=-999
      if(s(j).eq.99999)goto 111
      if(c(j).gt.7.5.and.c(j).le.12.5)qh2(j)=1010.0*1.230*s(j)
      if(c(j).le.7.5)goto 111
111   continue
c     for Ta>2.5
      do 112 j=1,nmax
      if(s(j).eq.99999)qh2(j)=-999
      if(s(j).eq.99999)goto 112
      if(c(j).gt.2.5.and.c(j).le.7.5) qh2(j)=1010.0*1.252*s(j)
      if(c(j).le.2.5) goto 112
112   continue
c     for Ta>-2.5
      do 113 j=1,nmax
      if(s(j).eq.99999)qh2(j)=-999
      if(s(j).eq.99999)goto 113
      if(c(j).gt.-2.5.and.c(j).le.2.5) qh2(j)=1010.0*1.275*s(j)
      if(c(j).le.-2.5)goto 113
113   continue
c     for Ta>-7.5
      do 114 j=1,nmax
      if(s(j).eq.99999)qh2(j)=-999
      if(s(j).eq.99999)goto 114
      if(c(j).gt.-7.5.and.c(j).le.-2.5) qh2(j)=1010.0*1.299*s(j)
      if(c(j).le.-7.5)goto 114
114   continue
c     for Ta>-12.5
      do 115 j=1,nmax
      if(s(j).eq.99999)qh2(j)=-999
      if(s(j).eq.99999)goto 115
      if(c(j).gt.-12.5.and.c(j).le.-7.5) qh2(j)=1010.0*1.324*s(j)
      if(c(j).le.-12.5)goto 115
115   continue
```

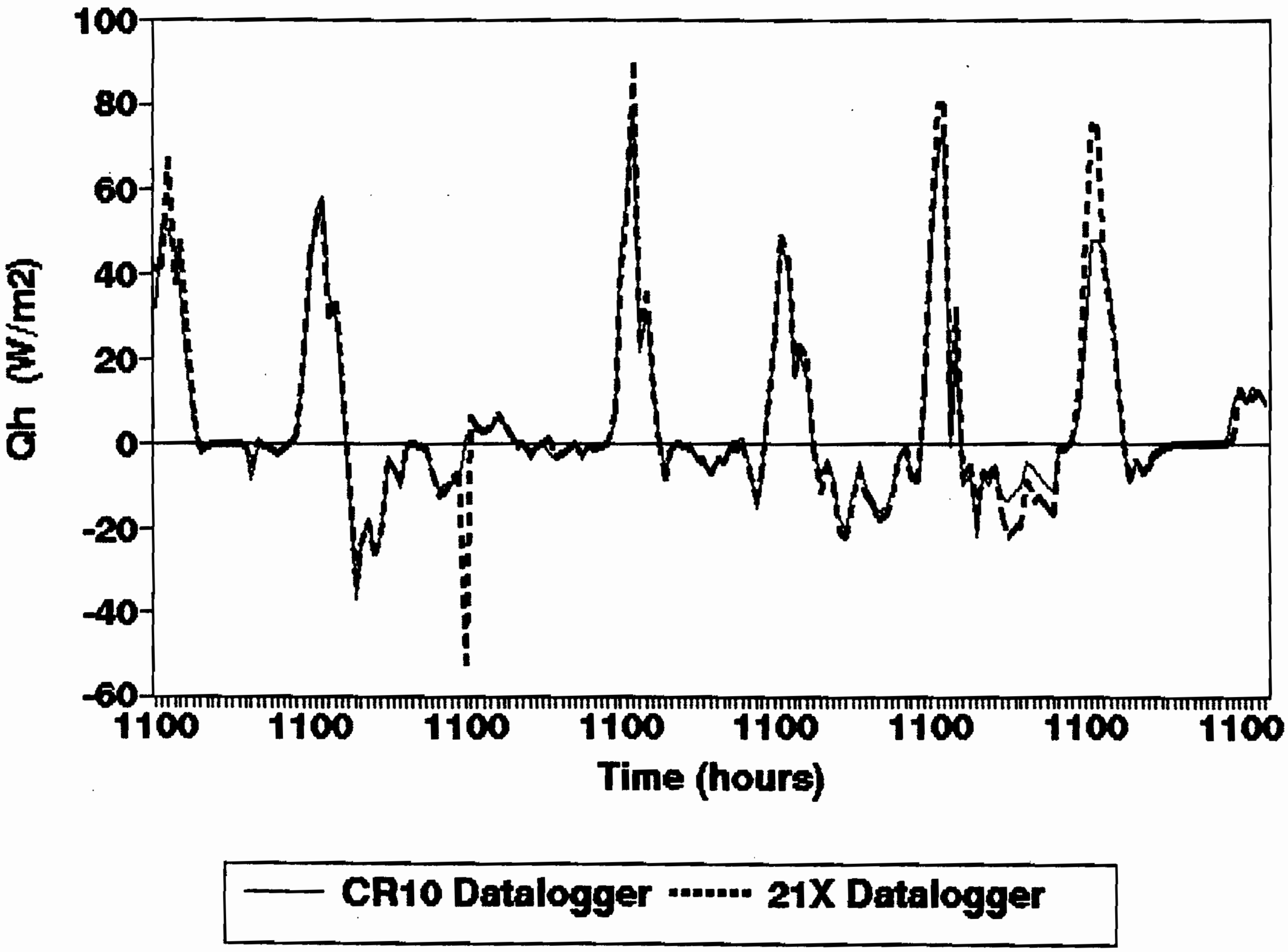
```
c       for Ta>-17.5
        do 116 j=1,nmax
        if(s(j).eq.99999)qh2(j)=-999
        if(s(j).eq.99999)goto 116
        if(c(j).gt.-17.5.and.c(j).le.-12.5) qh2(j)=1010.0*1.349*s(j)
        if(c(j).le.-17.5)goto 116
116     continue
c       for Ta>-22.5
        do 117 j=1,nmax
        if(s(j).eq.99999)qh2(j)=-999
        if(s(j).eq.99999)goto 117
        if(c(j).gt.-22.5.and.c(j).le.-17.5) qh2(j)=1010.0*1.376*s(j)
        if(c(j).le.-22.5)goto 117
117     continue
c       for Ta>-27.5
        do 118 j=1,nmax
        if(s(j).eq.99999)qh2(j)=-999
        if(s(j).eq.99999)goto 118
        if(c(j).gt.-27.5.and.c(j).le.-22.5) qh2(j)=1010.0*1.404*s(j)
        if(c(j).le.-27.5)goto 118
118     continue
c       for Ta<-27.5
        do 119 j=1,nmax
        if (s(j).eq.-99999)qh2(j)=-999
        if (s(j).eq.-99999)goto 119
        if(c(j).le.-27.5)qh2(j)=1010.0*1.433*s(j)
119     continue
c       writing in file
        do 20 j=1,nmax
        write(*,*)d(j),t(j),qh1(j),qh2(j)
        write(7,100)d(j),t(j),w(j),s(j),u(j),qh1(j),qh2(j),c(j),y(j),
     *r(j),a1(j),a2(j),b1(j),b2(j),o(j),q(j)
20      continue
100   format(f5.1,1x,f6.1,f12.5,1x,f12.5,1x,f12.5,1x,f8.2,1x,f8.2,1x,
     *f10.2,1x,f10.2,1x,f10.2,1x,f12.5,1x,f12.5,1x,f12.5,1x,f12.5,1x,
     * f12.5,1x,f12.5)
        stop
        end
```

APPENDIX 3

CR10 Datalogger



CR10 & 21X Dataloggers



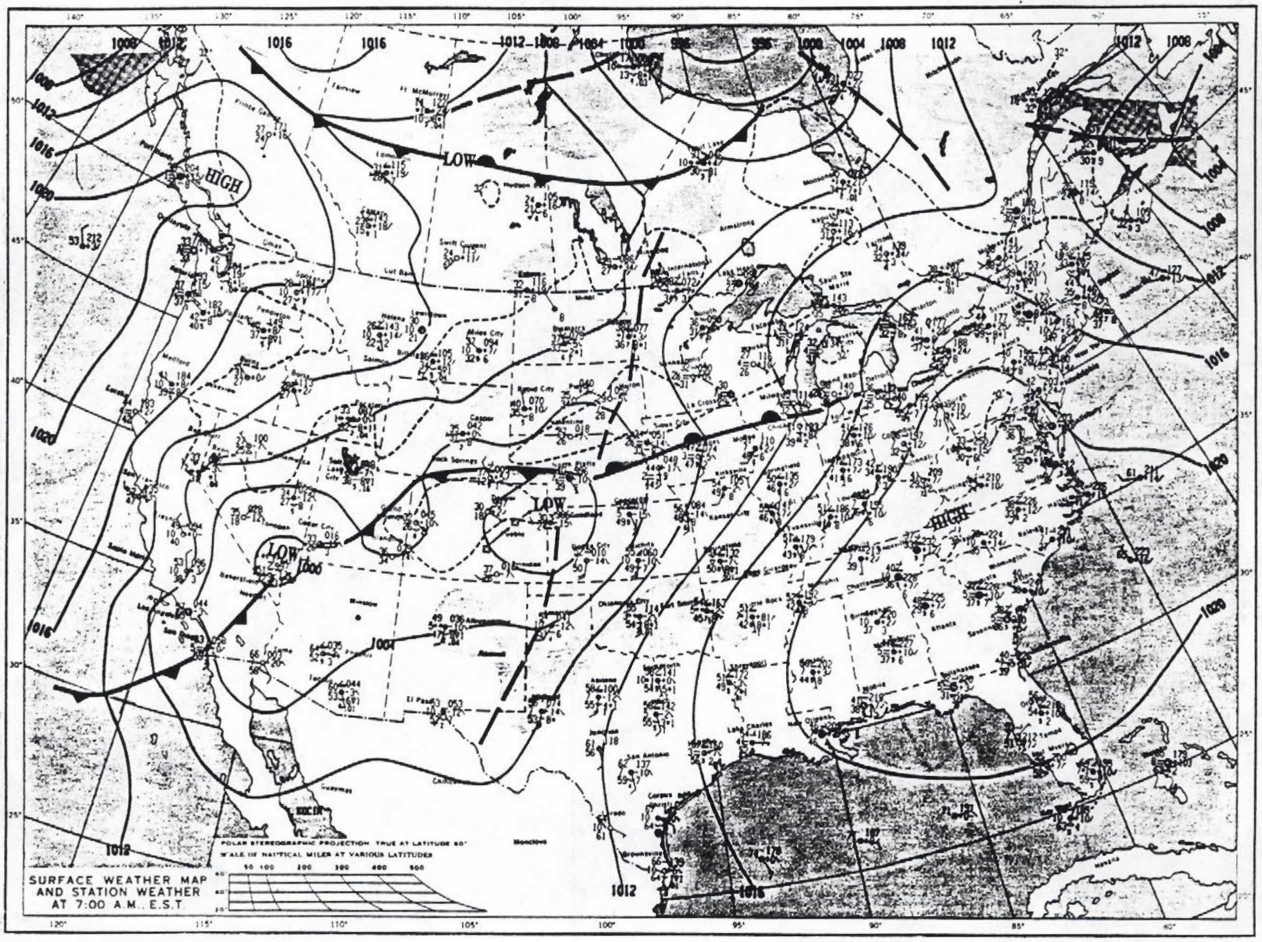
Appendix 3: Test Summaries

	Thermocouple #1 versus Thermocouple #2 (CR10 Datalogger)	21X versus CR10 Datalogger
R^2	0.98	0.92
Average Difference ($W\ m^{-2}$)	1.45	2.79

APPENDIX 4

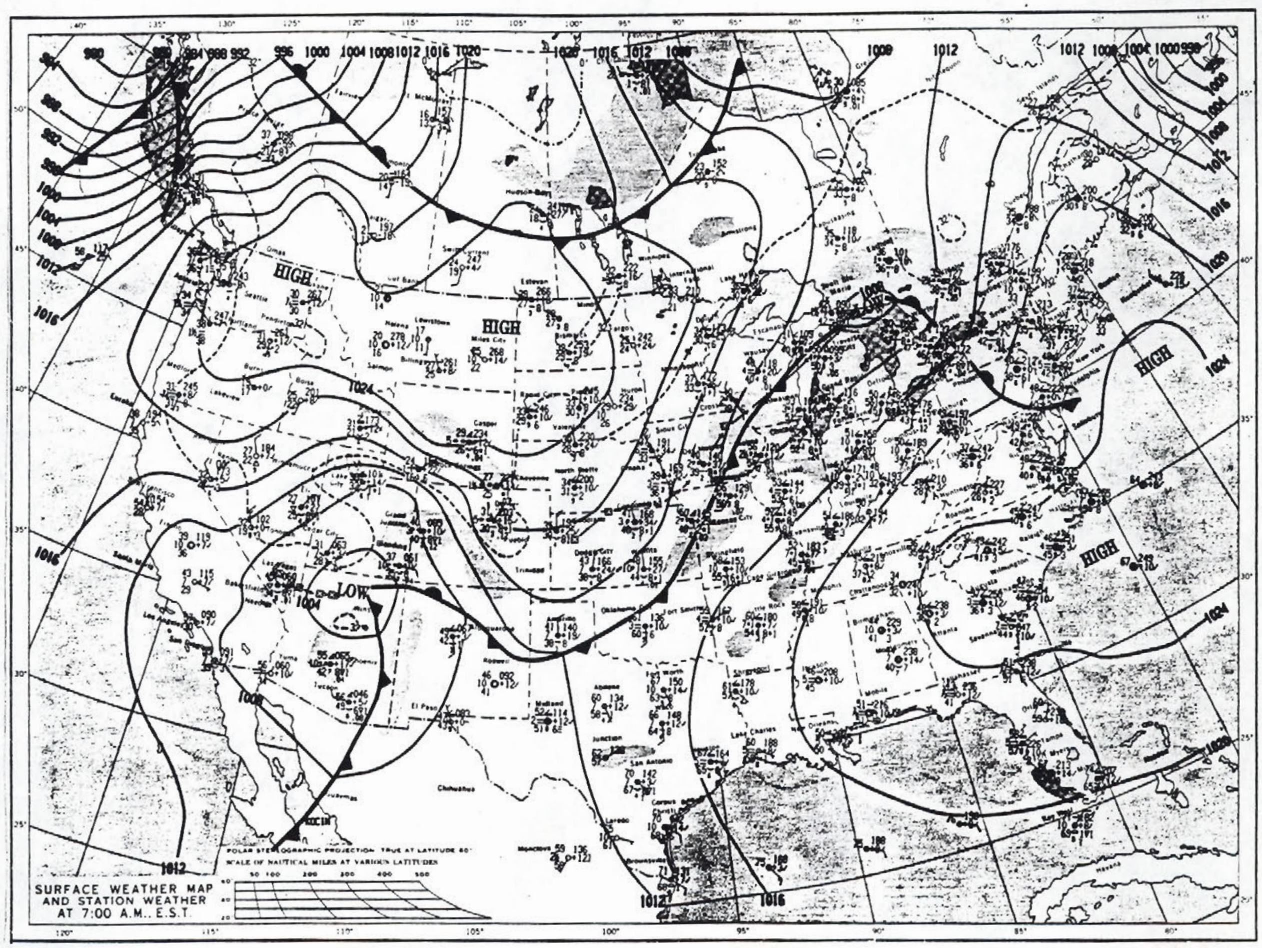
Synoptic maps of the case study days, as well as one day preceeding and one day following each case study day. (from the National Oceanic and Atmospheric Administration, 1991 and 1992)

THURSDAY, NOVEMBER 14, 1991

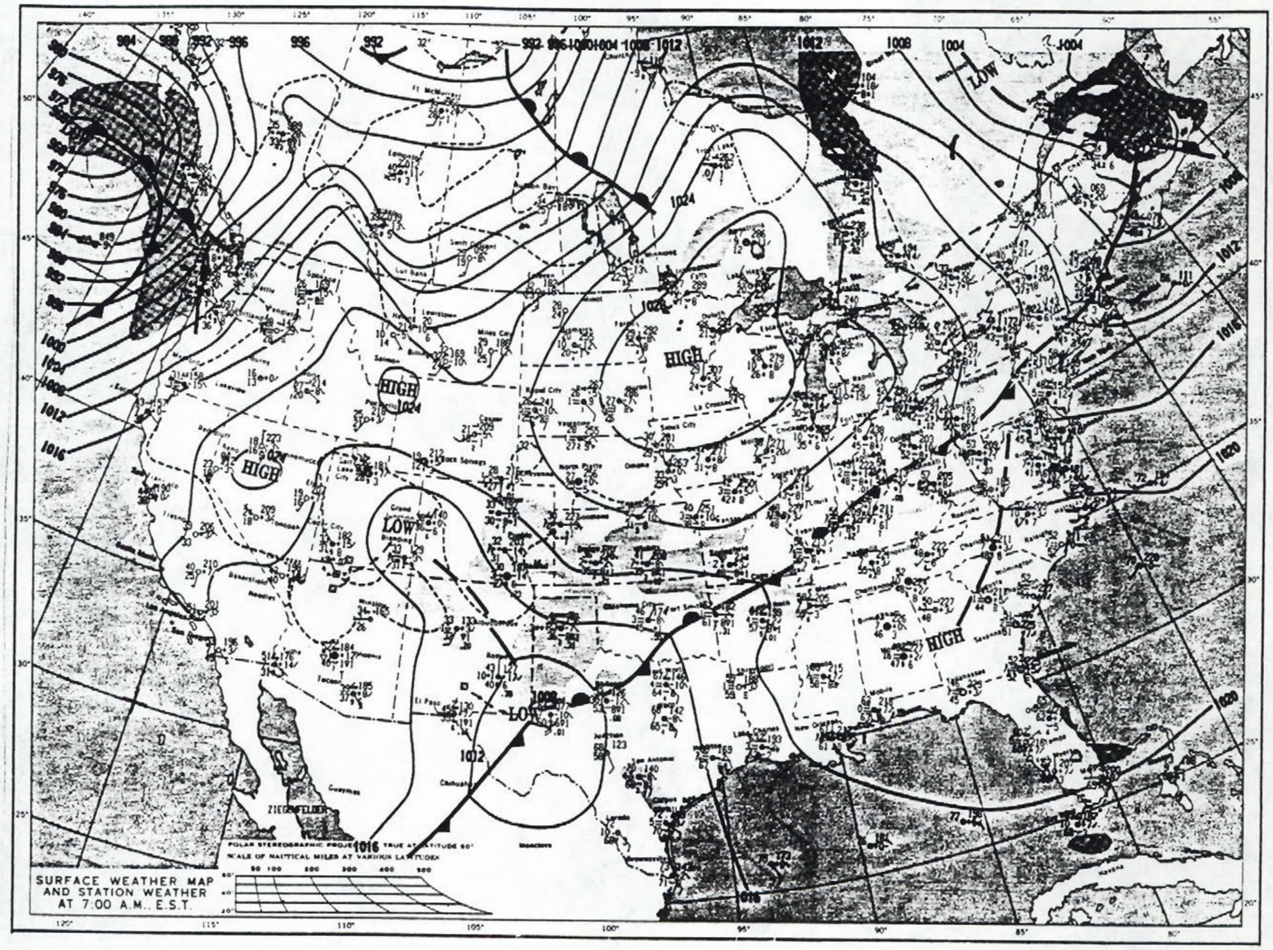


blurry print + end

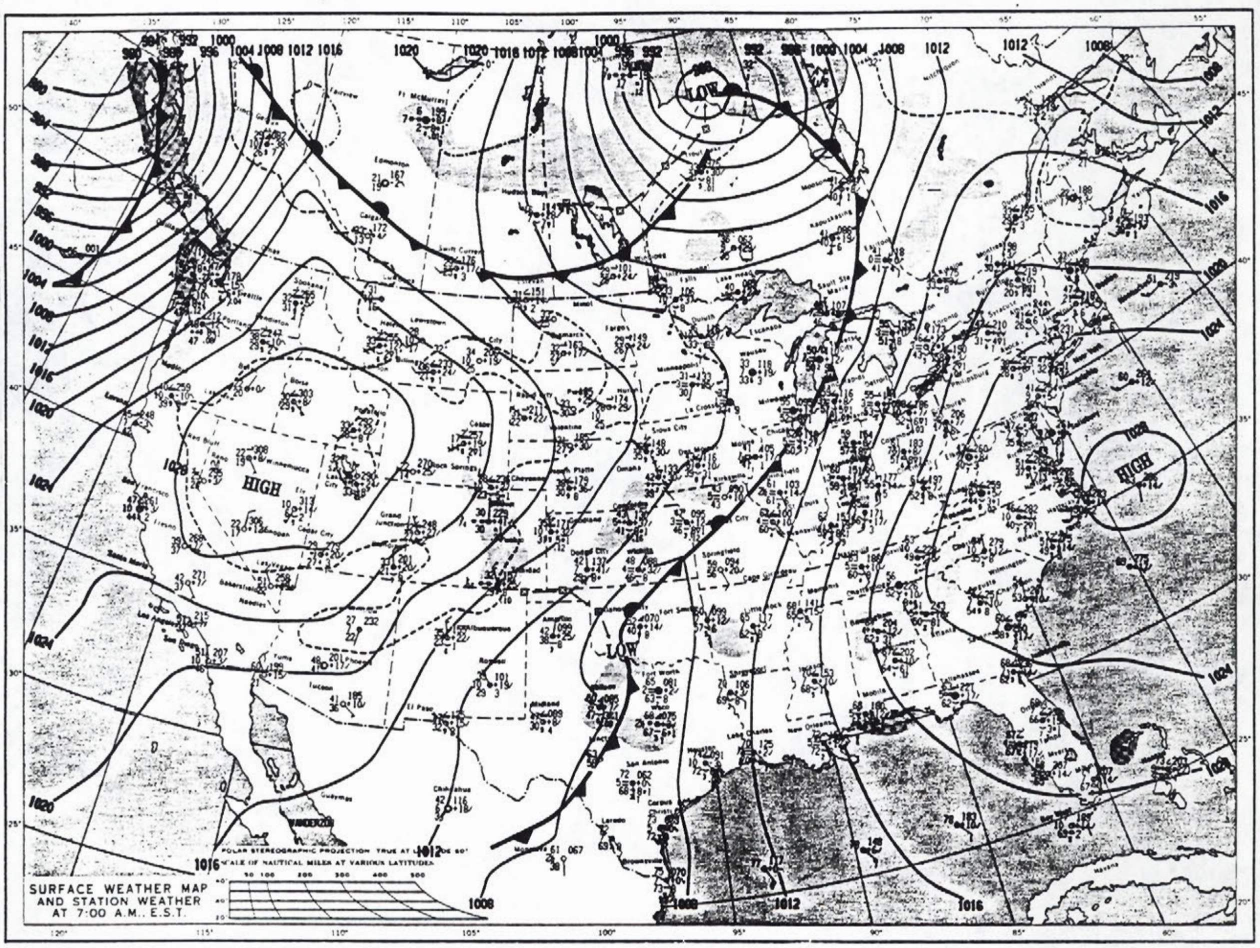
FRIDAY, NOVEMBER 15, 1991



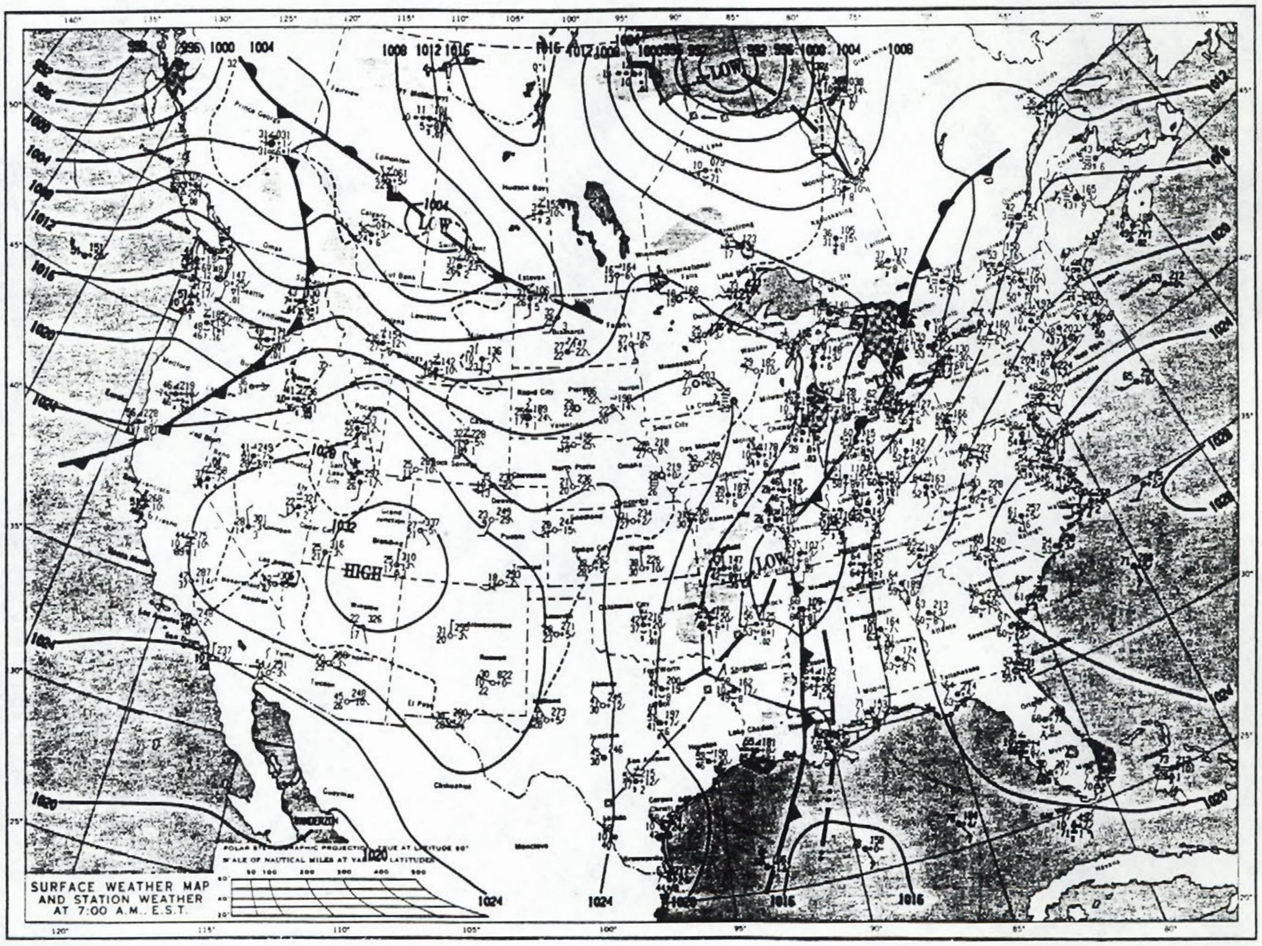
SATURDAY, NOVEMBER 16, 1991



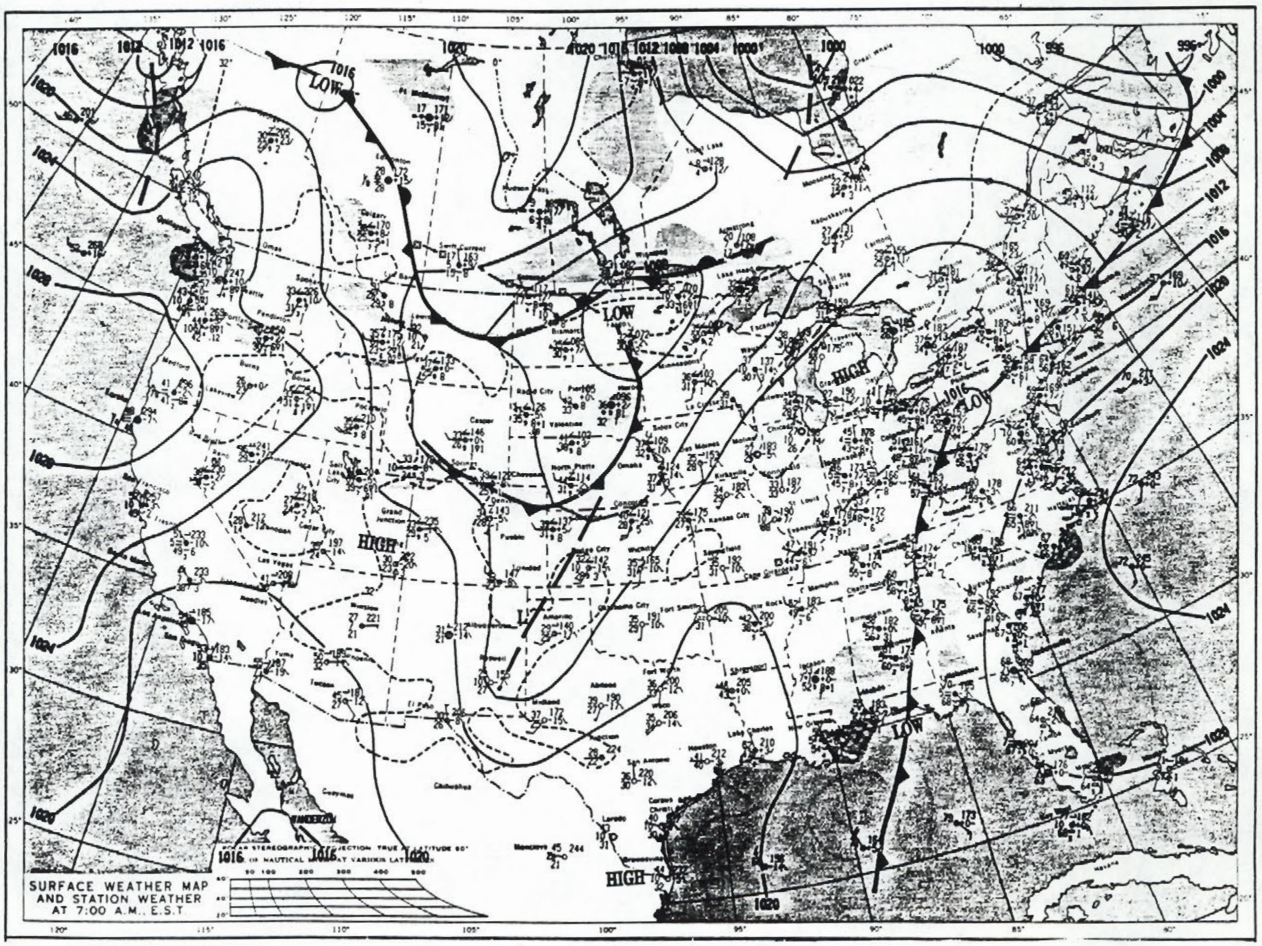
TUESDAY, NOVEMBER 19, 1991



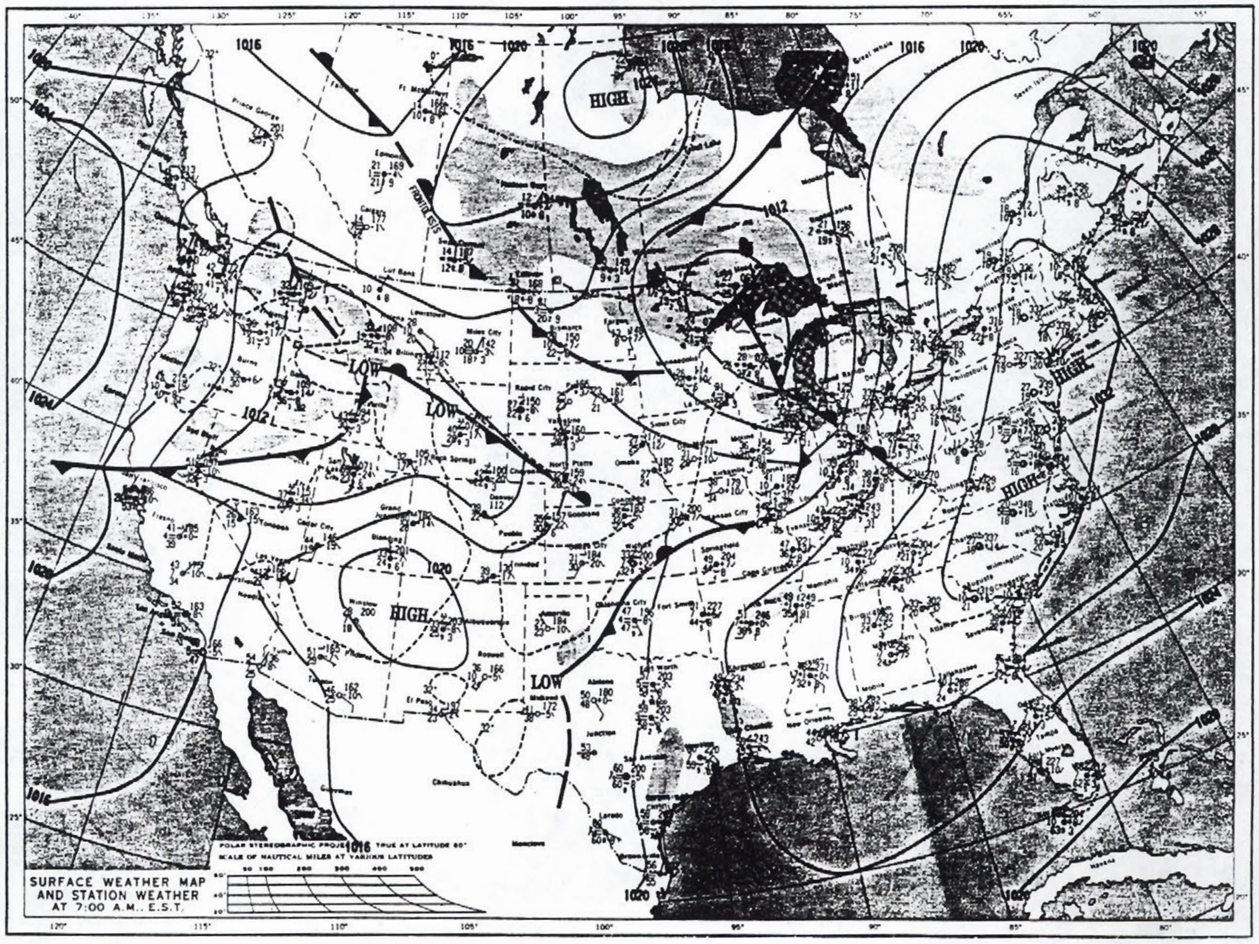
WEDNESDAY, NOVEMBER 20, 1991



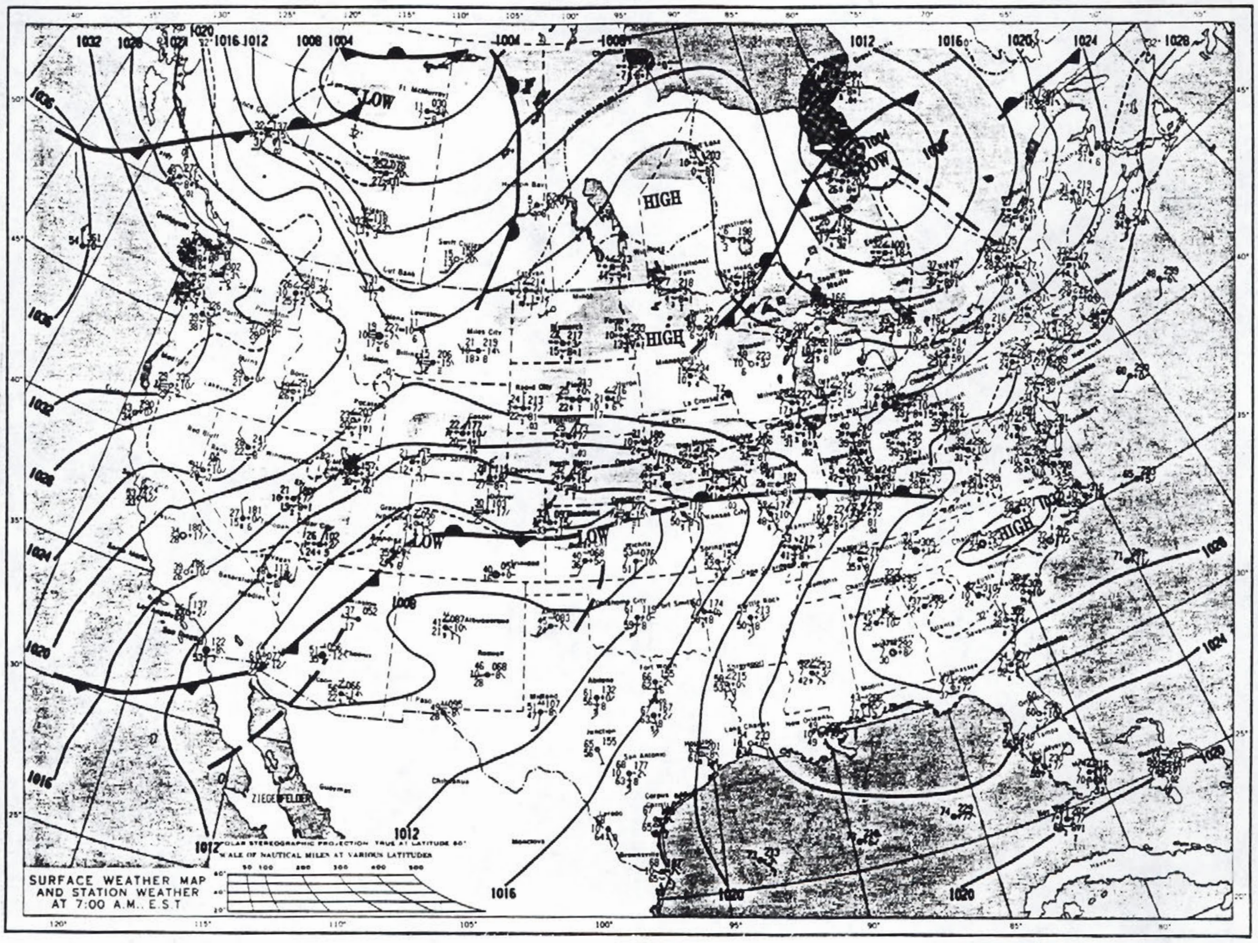
THURSDAY, NOVEMBER 21, 1991



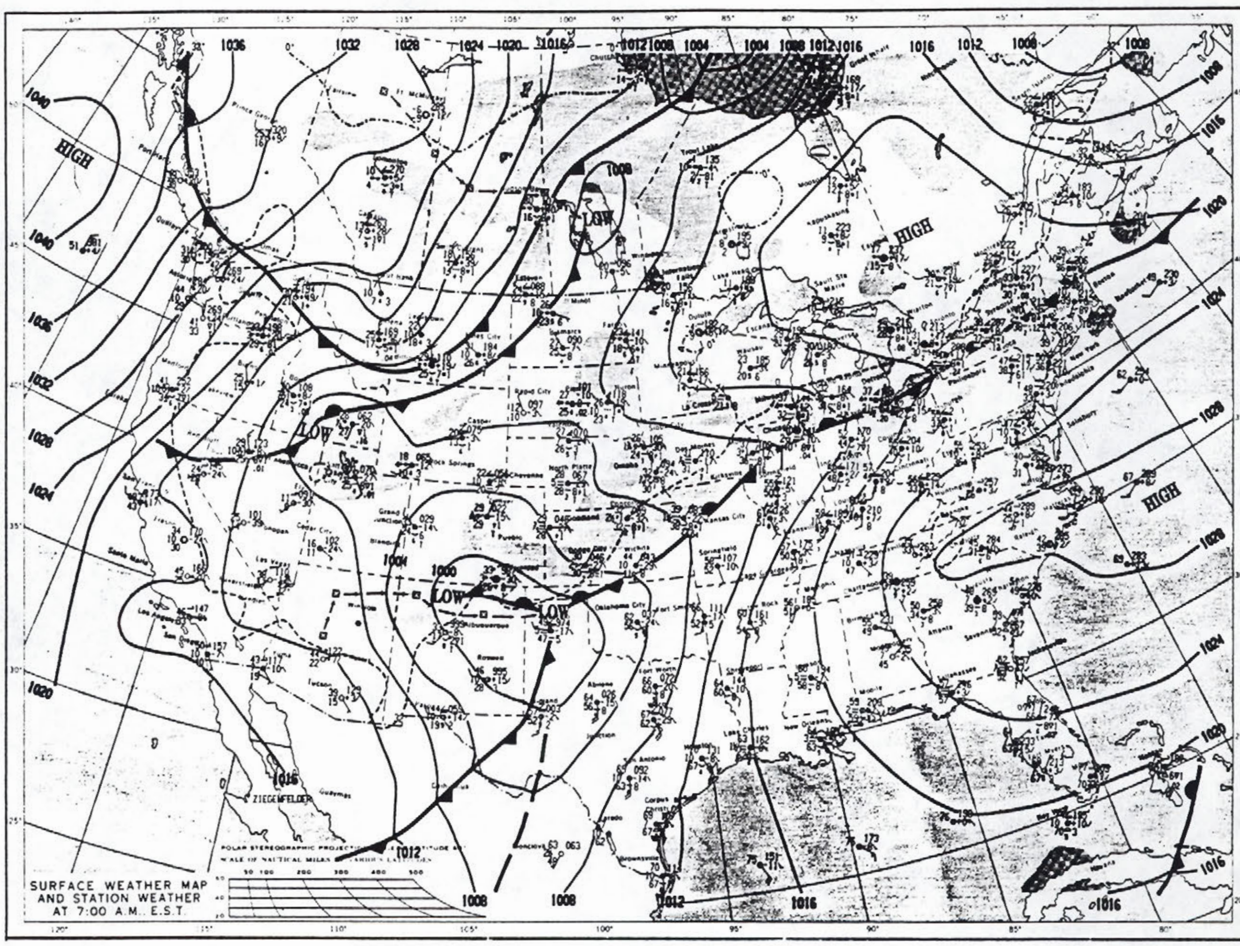
WEDNESDAY, NOVEMBER 27, 1991



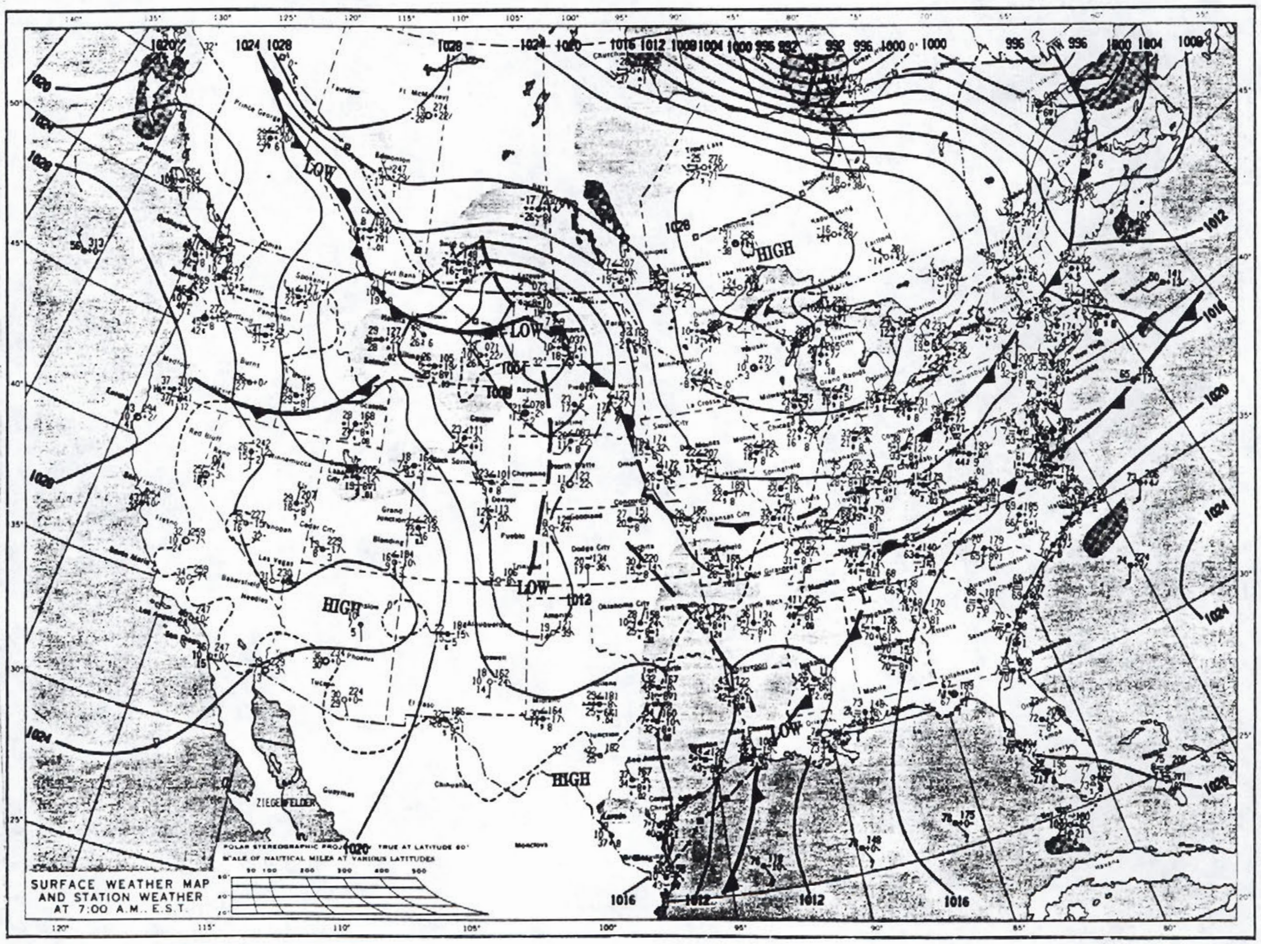
THURSDAY, NOVEMBER 28, 1991



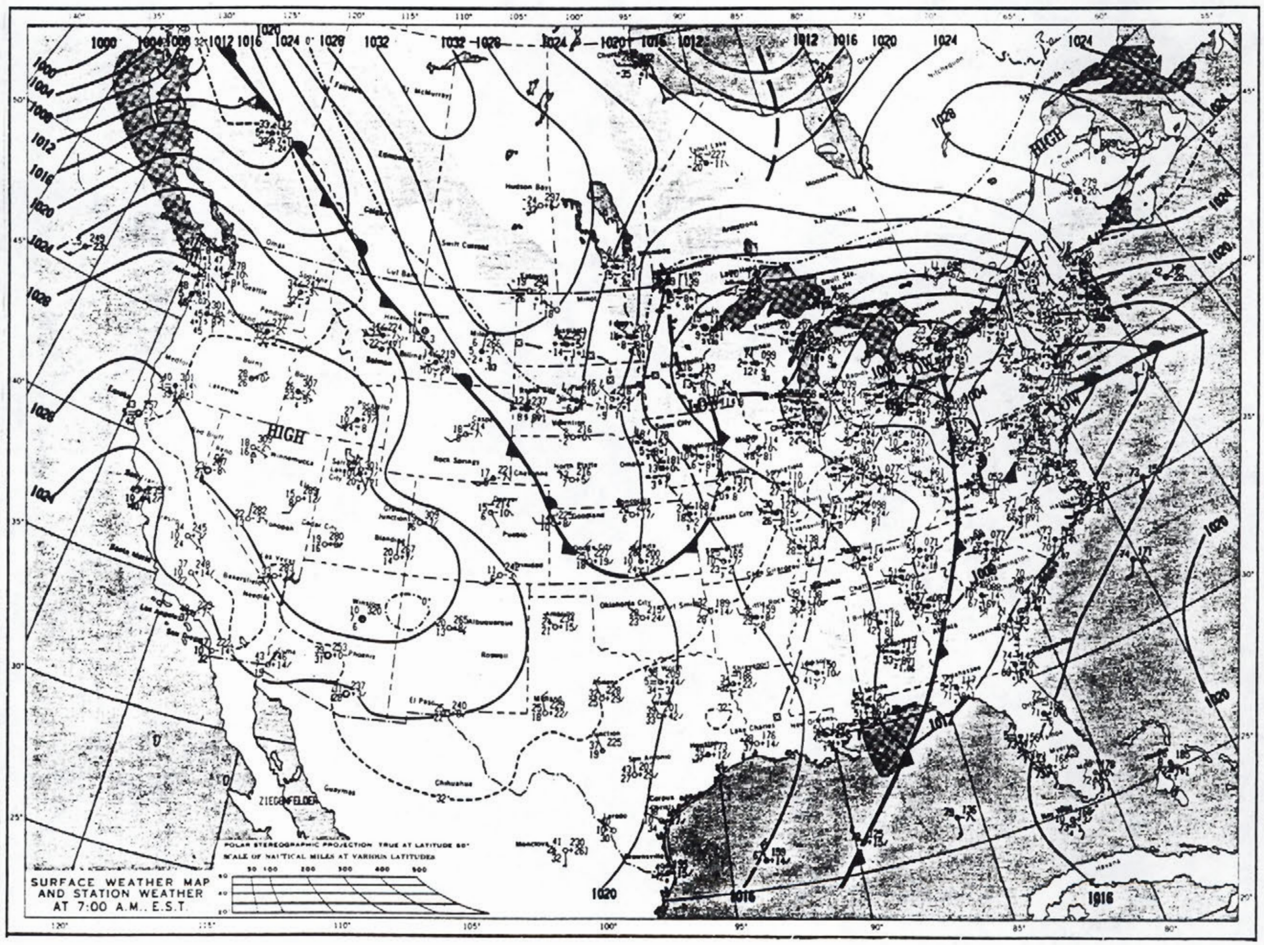
FRIDAY, NOVEMBER 29, 1991



MONDAY, DECEMBER 2, 1991

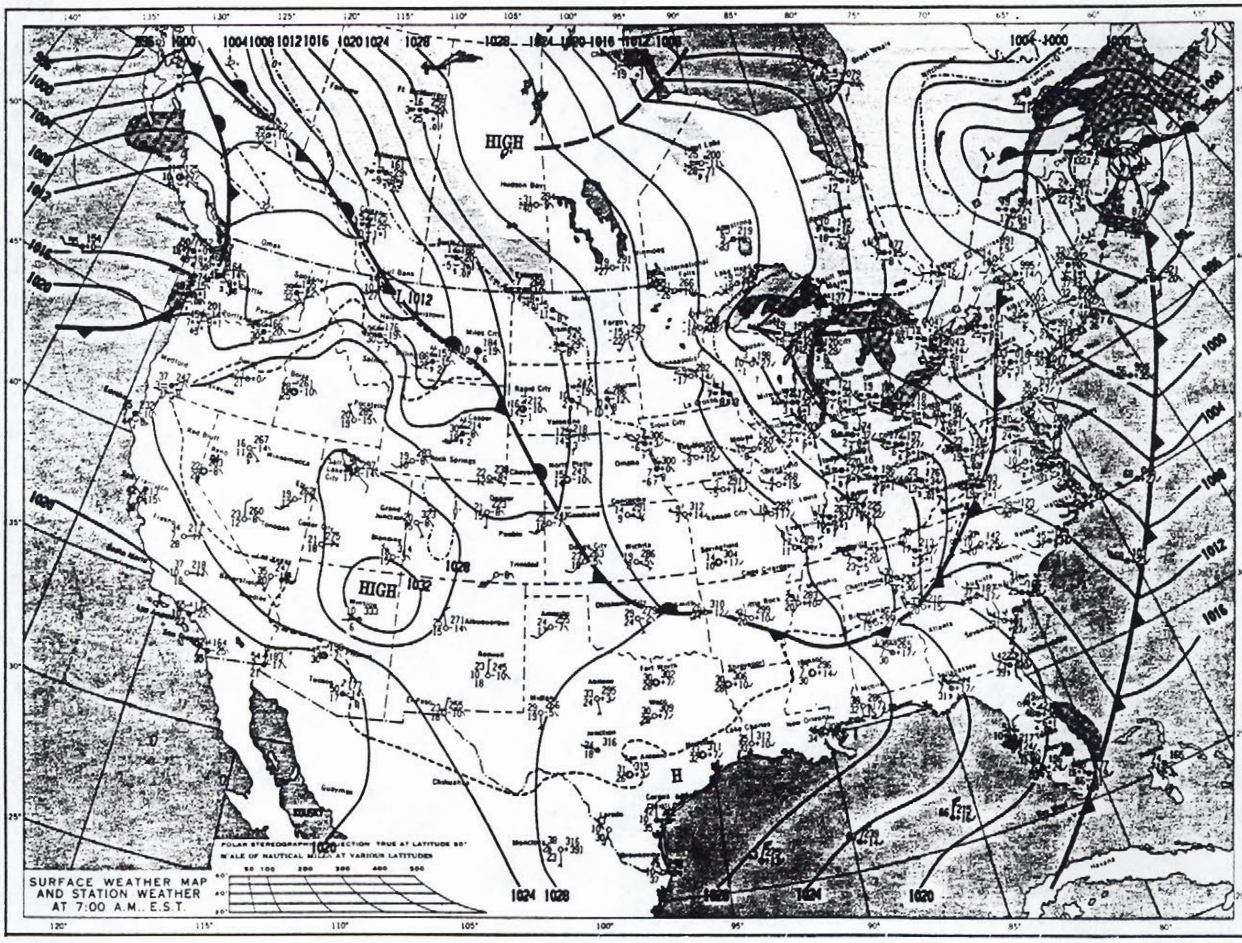


TUESDAY, DECEMBER 3, 1991

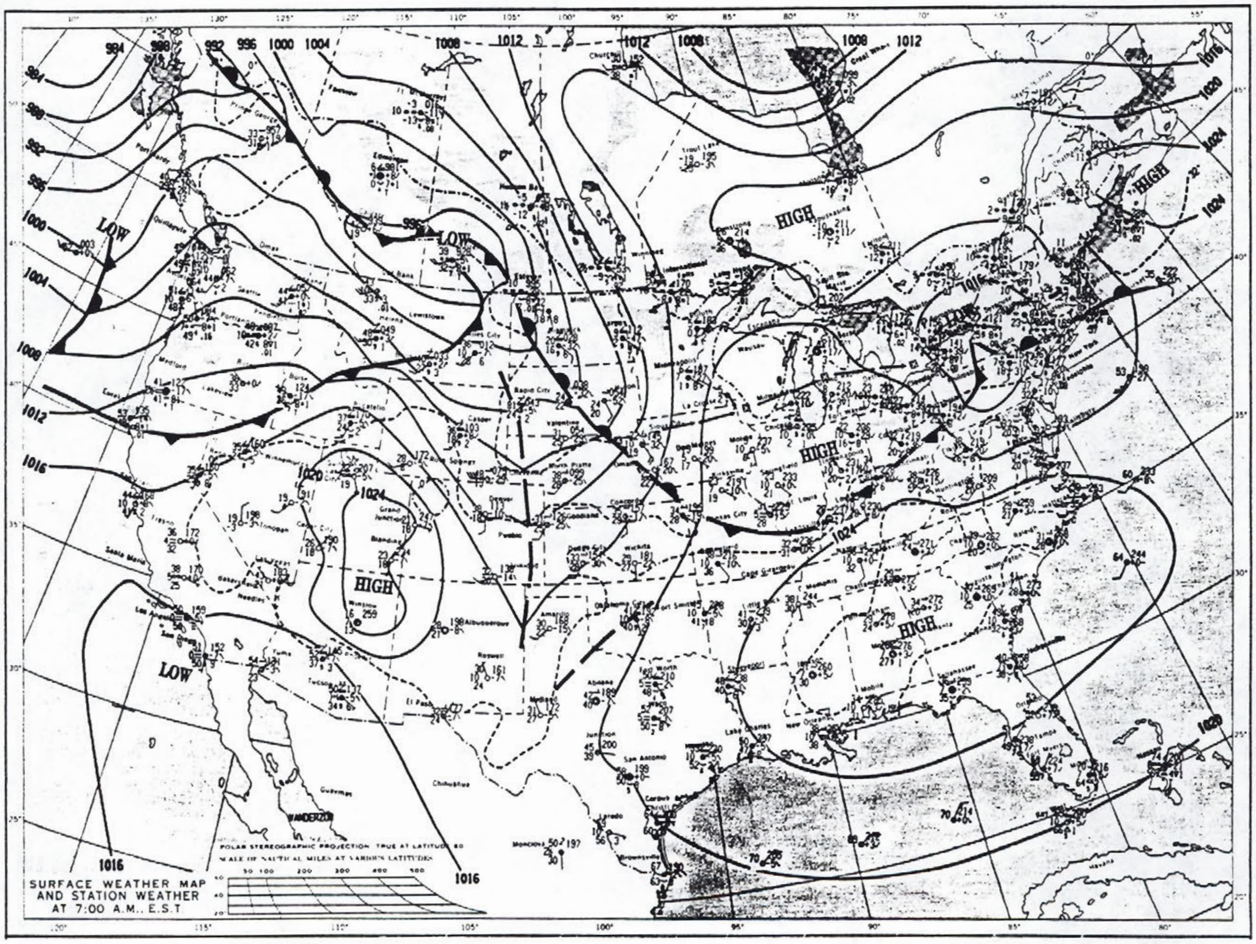


SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M., E.S.T.

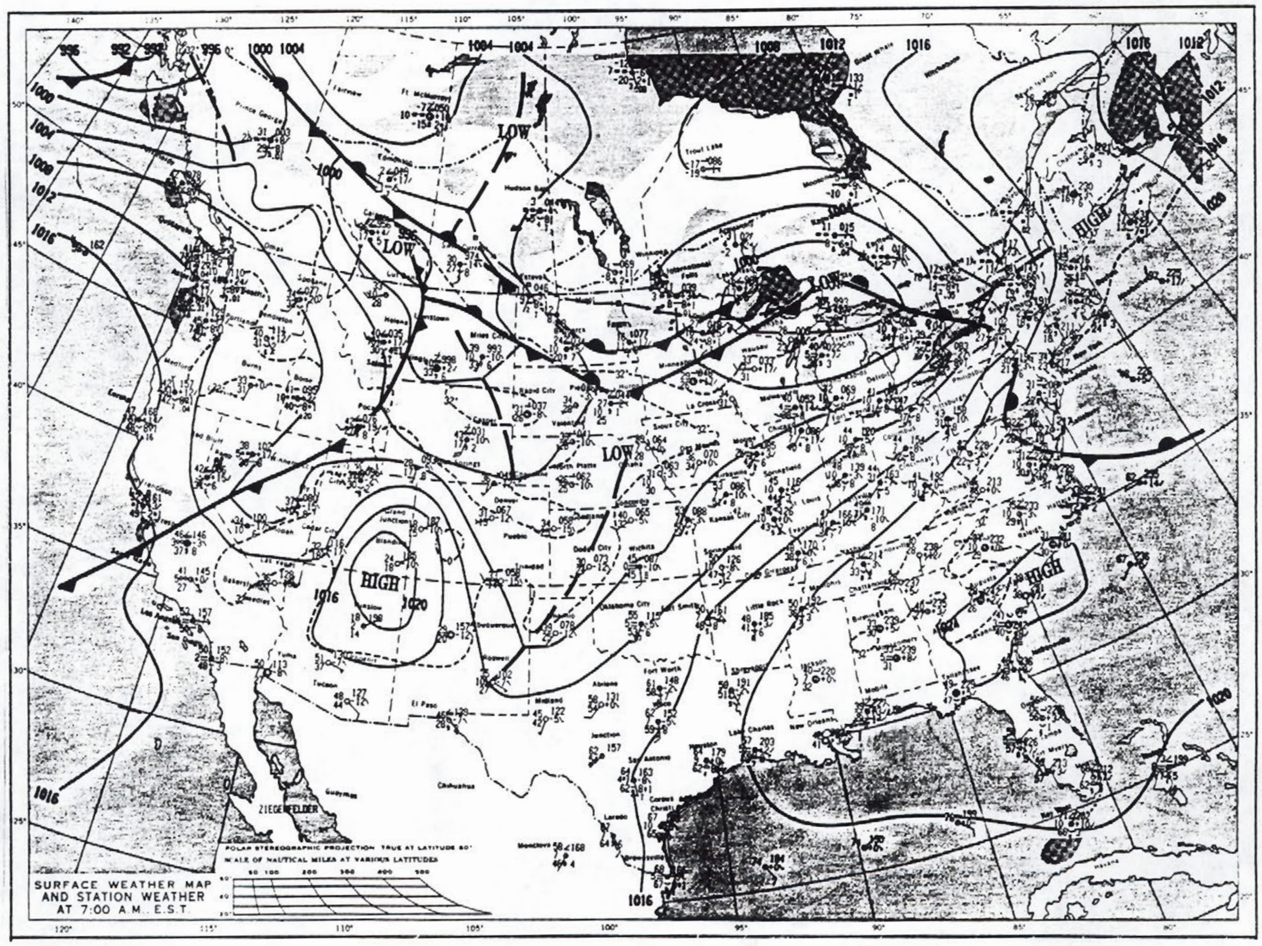
WEDNESDAY, DECEMBER 4, 1991



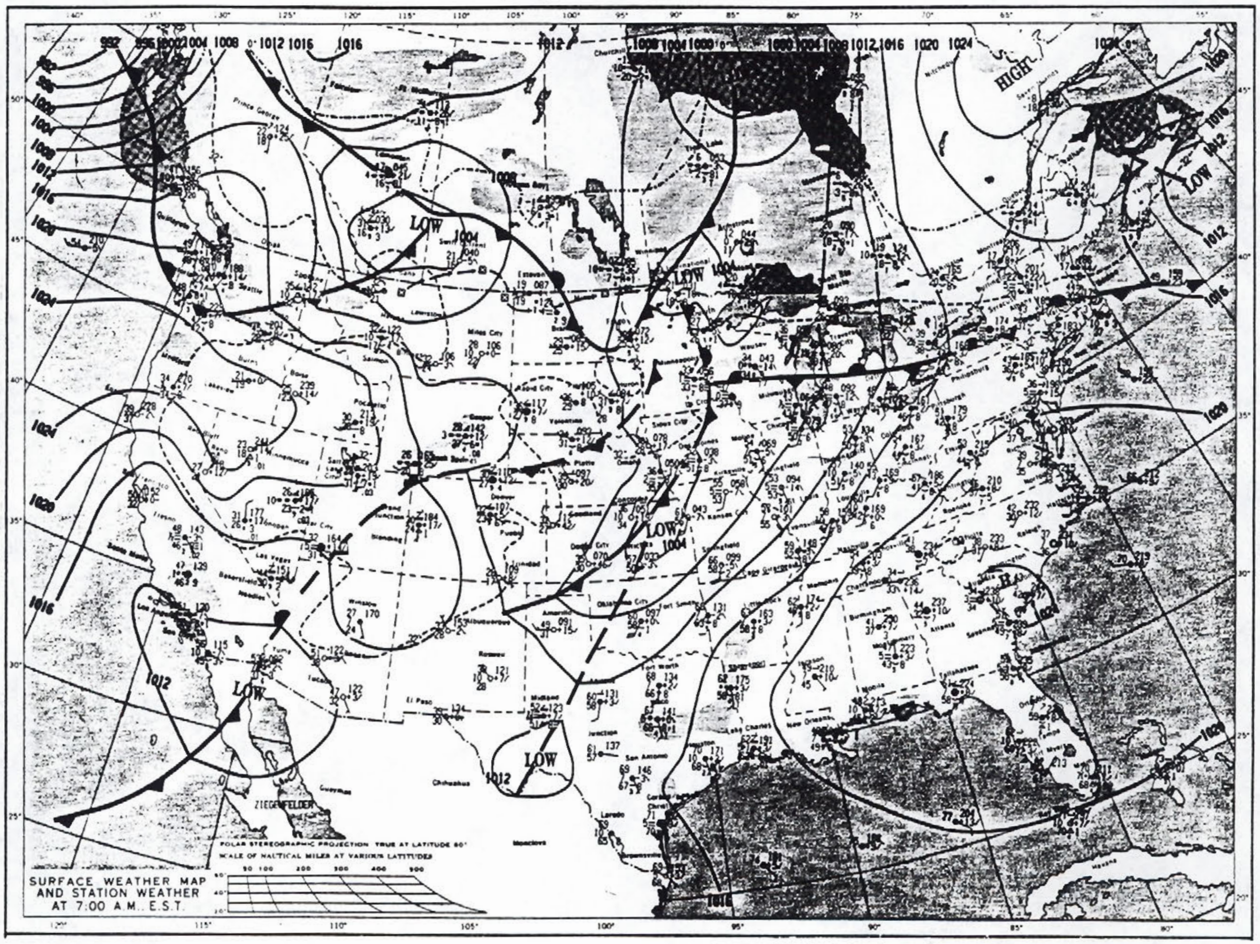
FRIDAY, DECEMBER 6, 1991



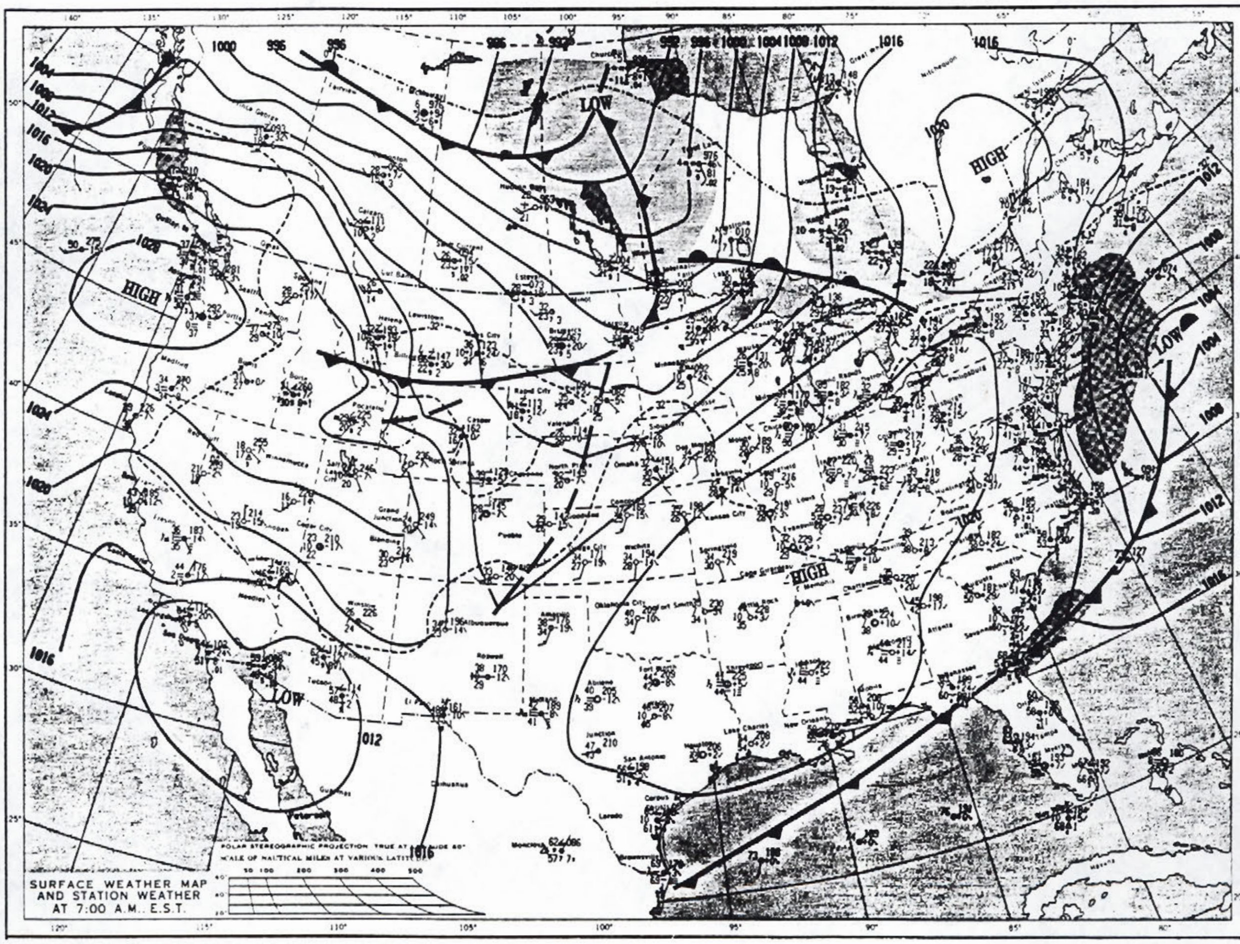
SATURDAY, DECEMBER 7, 1991



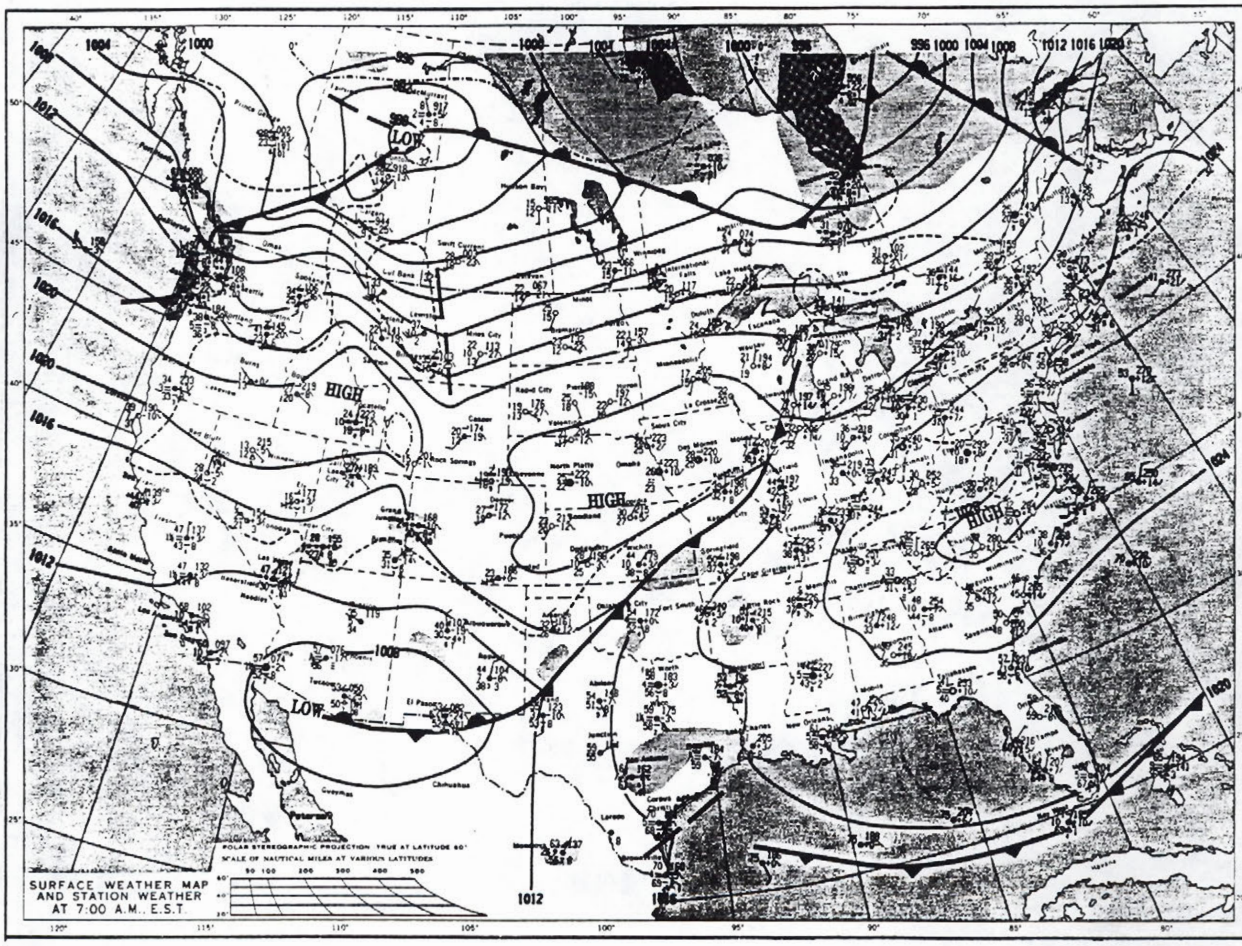
SUNDAY, DECEMBER 8, 1991



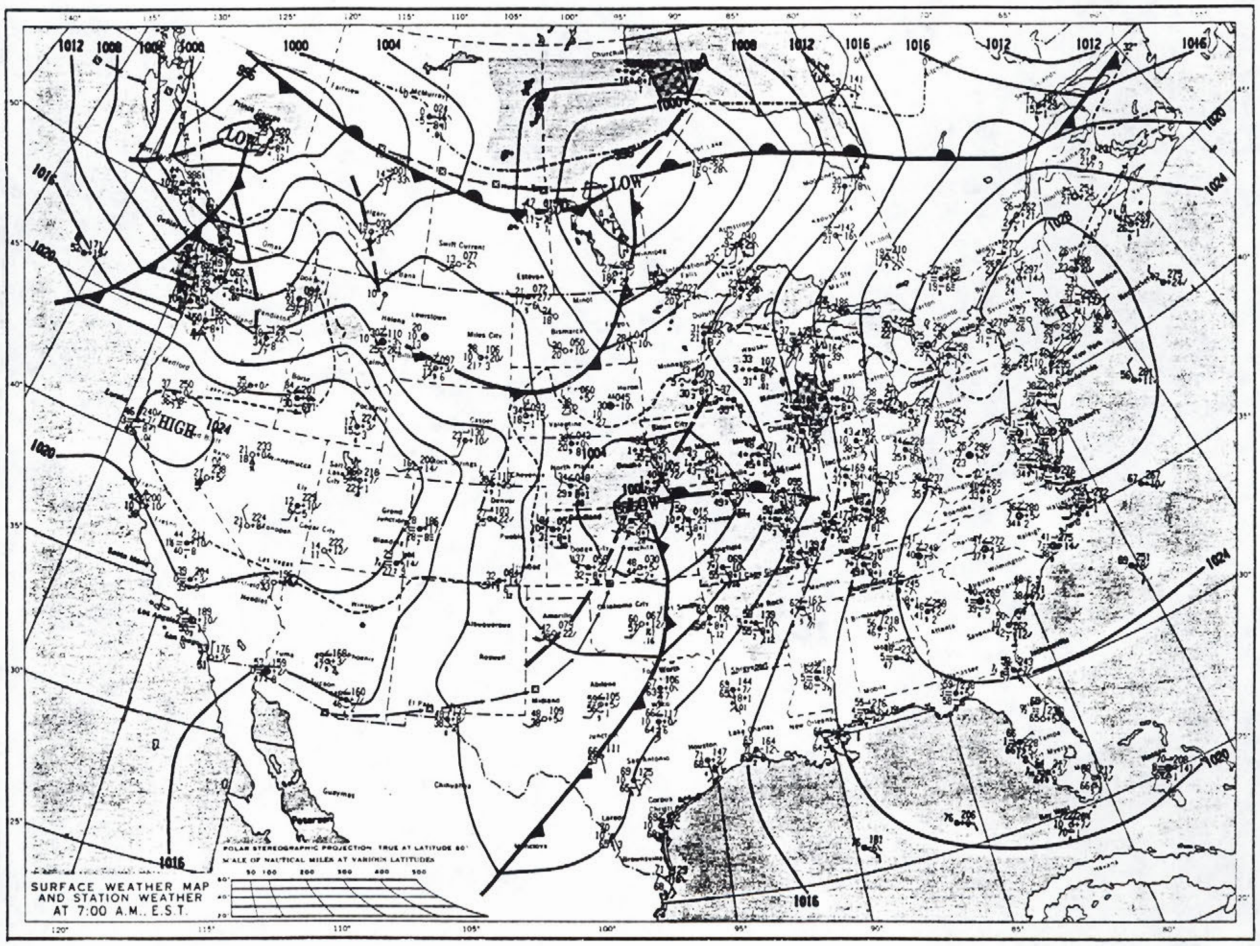
TUESDAY, DECEMBER 10, 1991



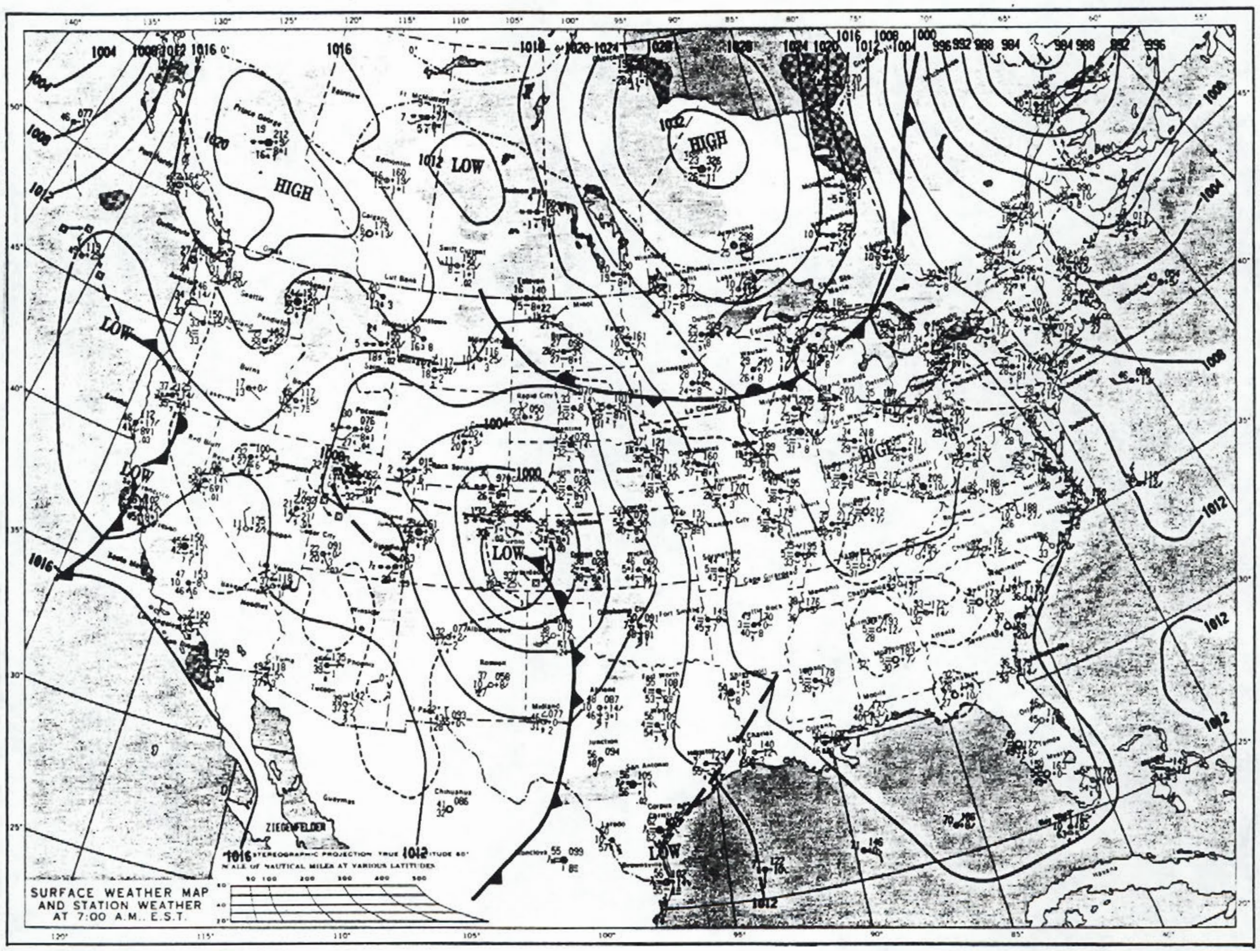
WEDNESDAY, DECEMBER 11, 1991



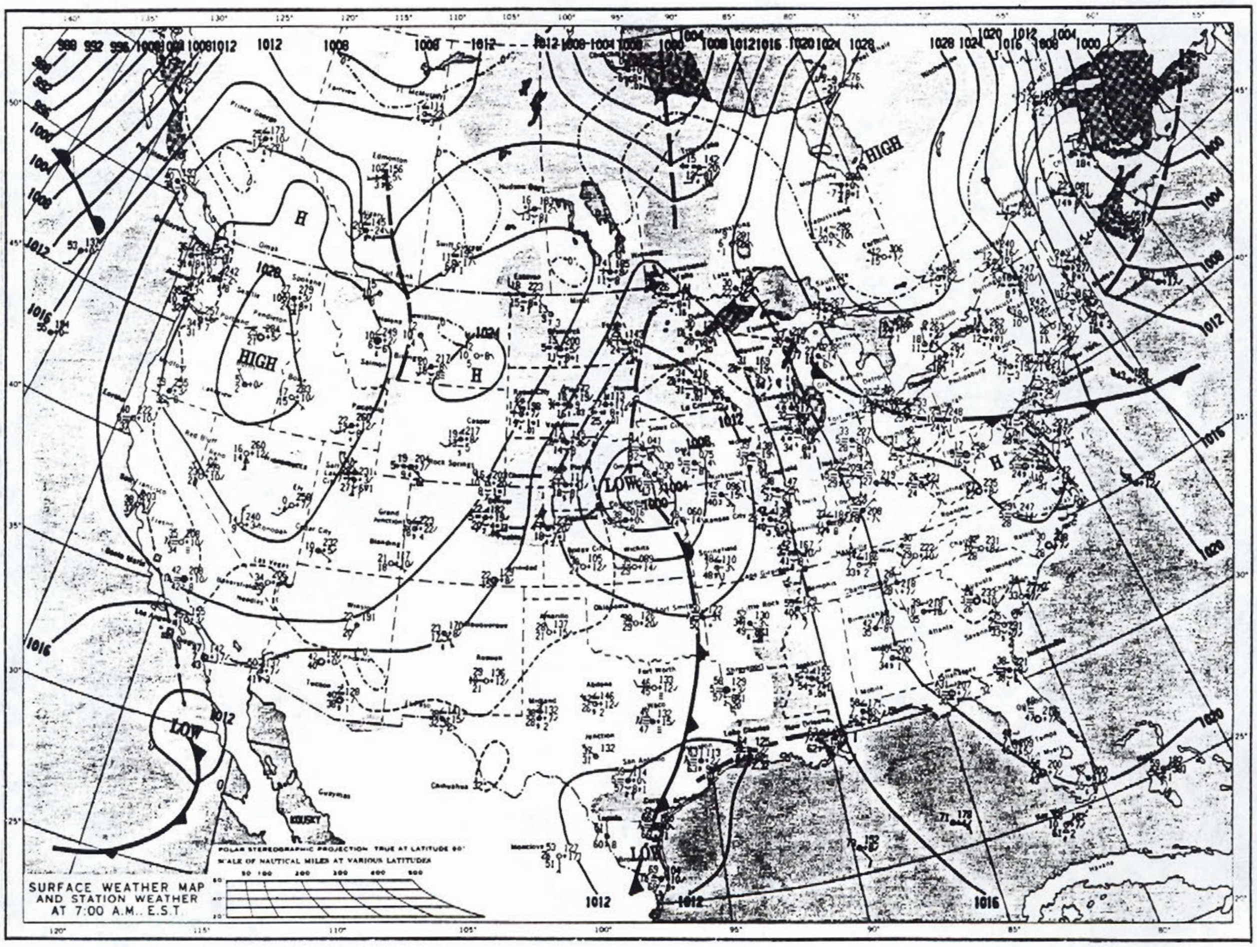
THURSDAY, DECEMBER 12, 1991



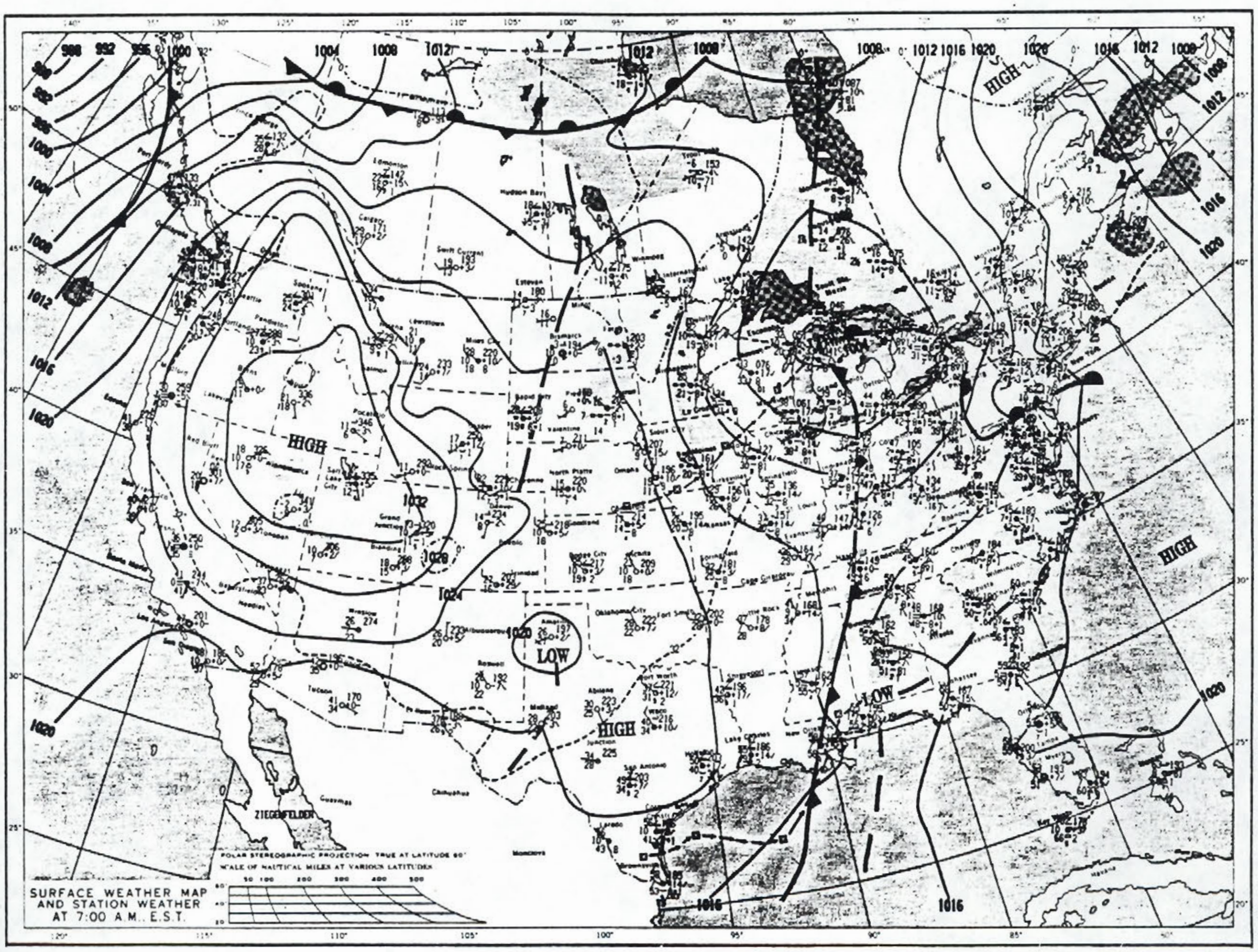
TUESDAY, JANUARY 7, 1992



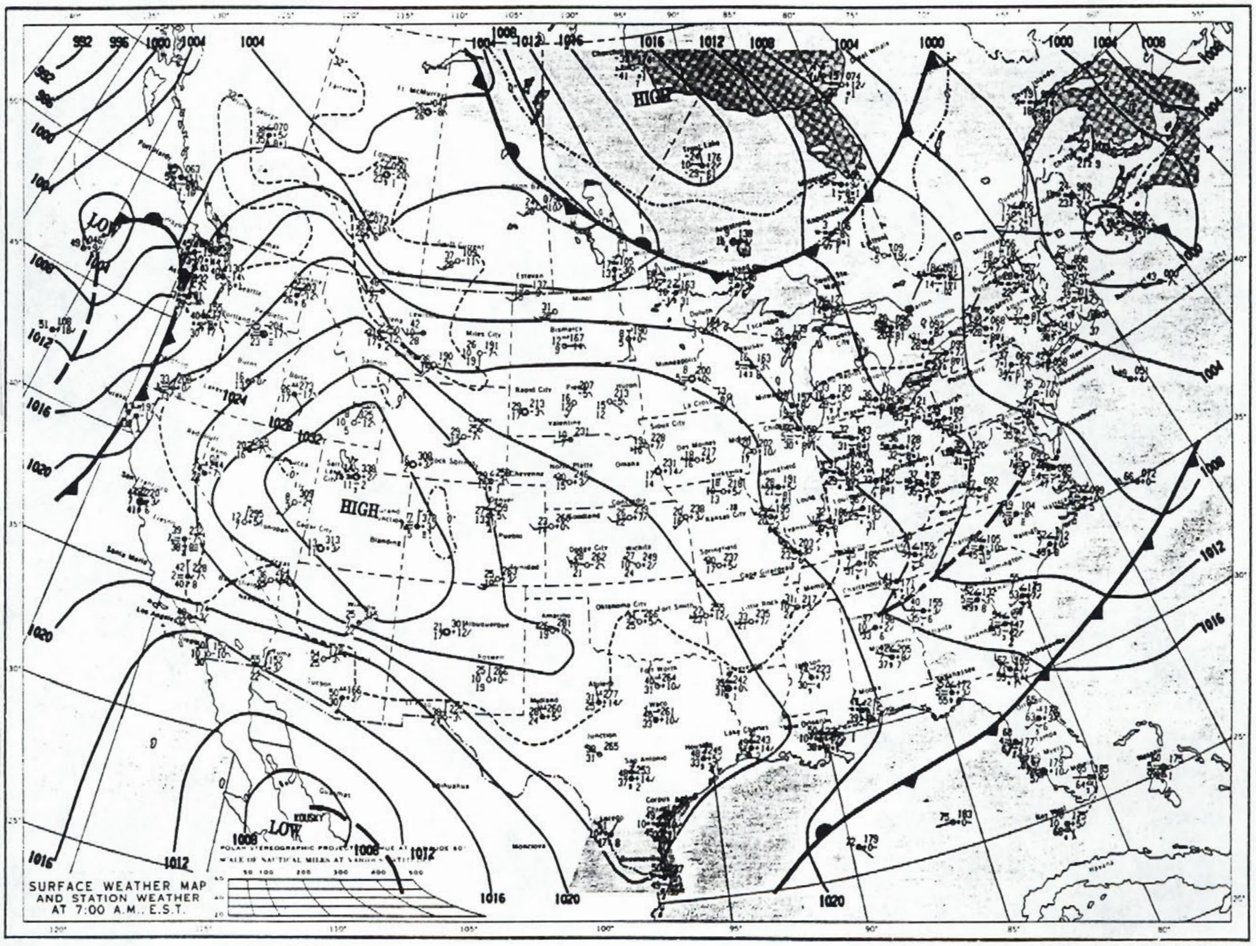
WEDNESDAY, JANUARY 8, 1992



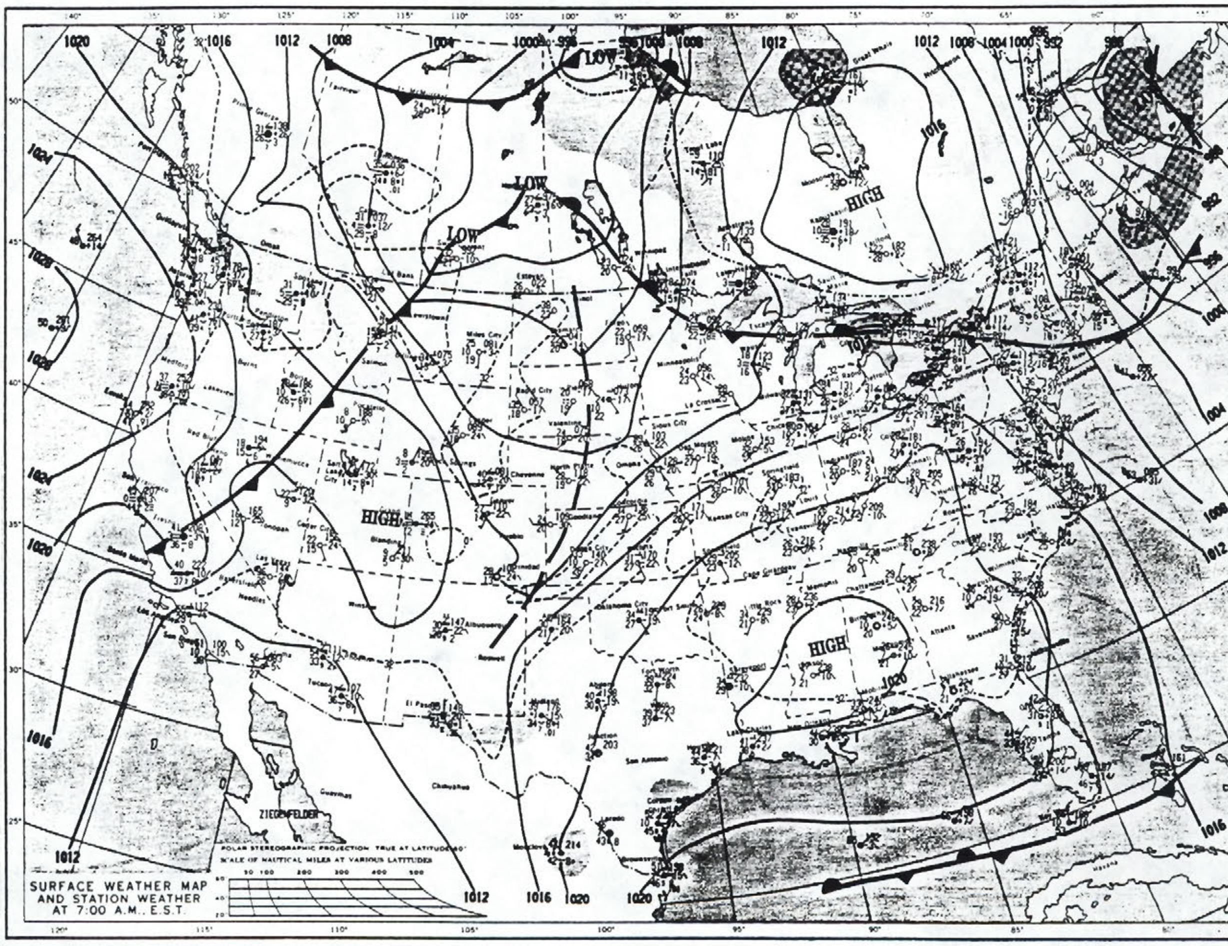
THURSDAY, JANUARY 9, 1992



FRIDAY, JANUARY 10, 1992

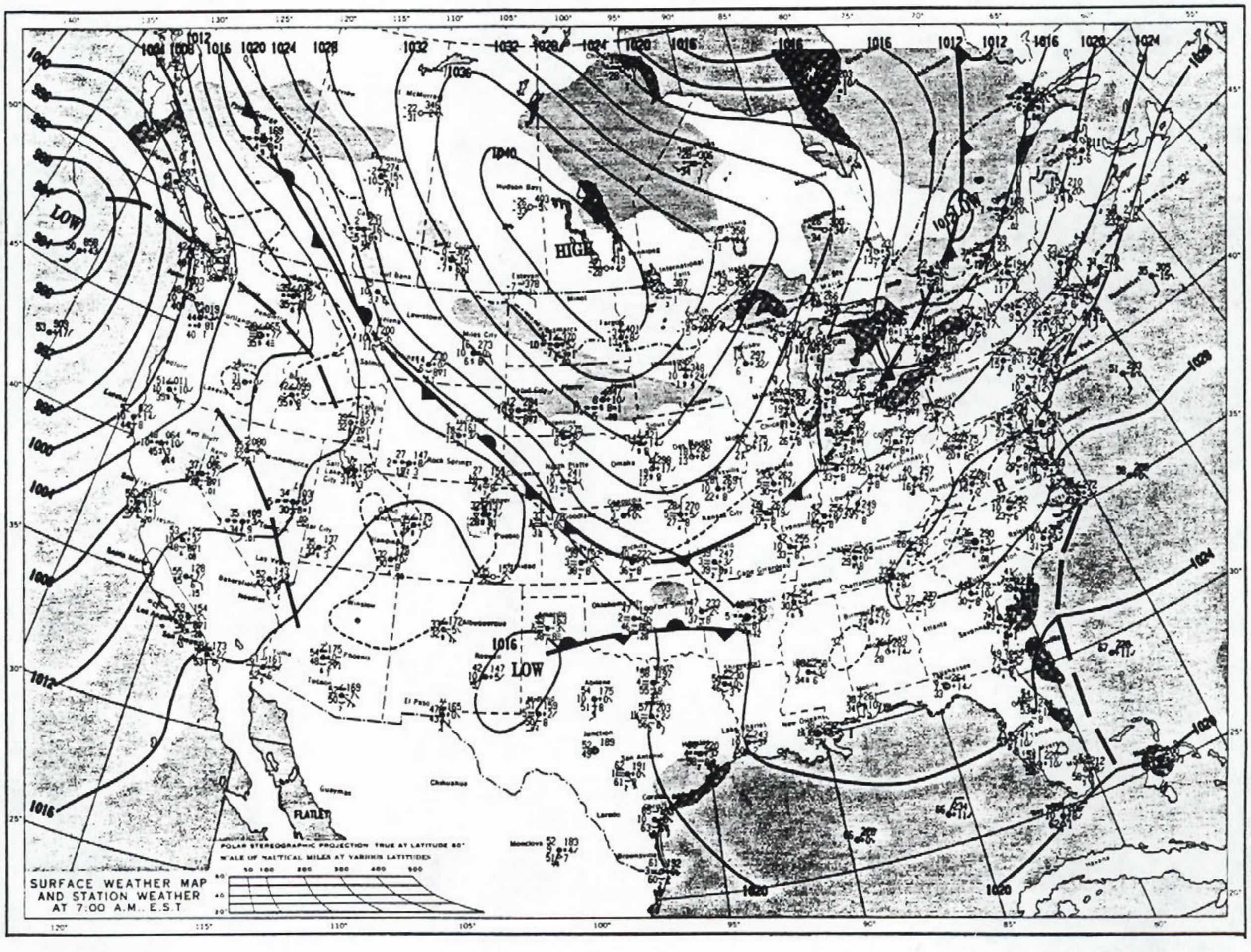


SATURDAY, JANUARY 11, 1992

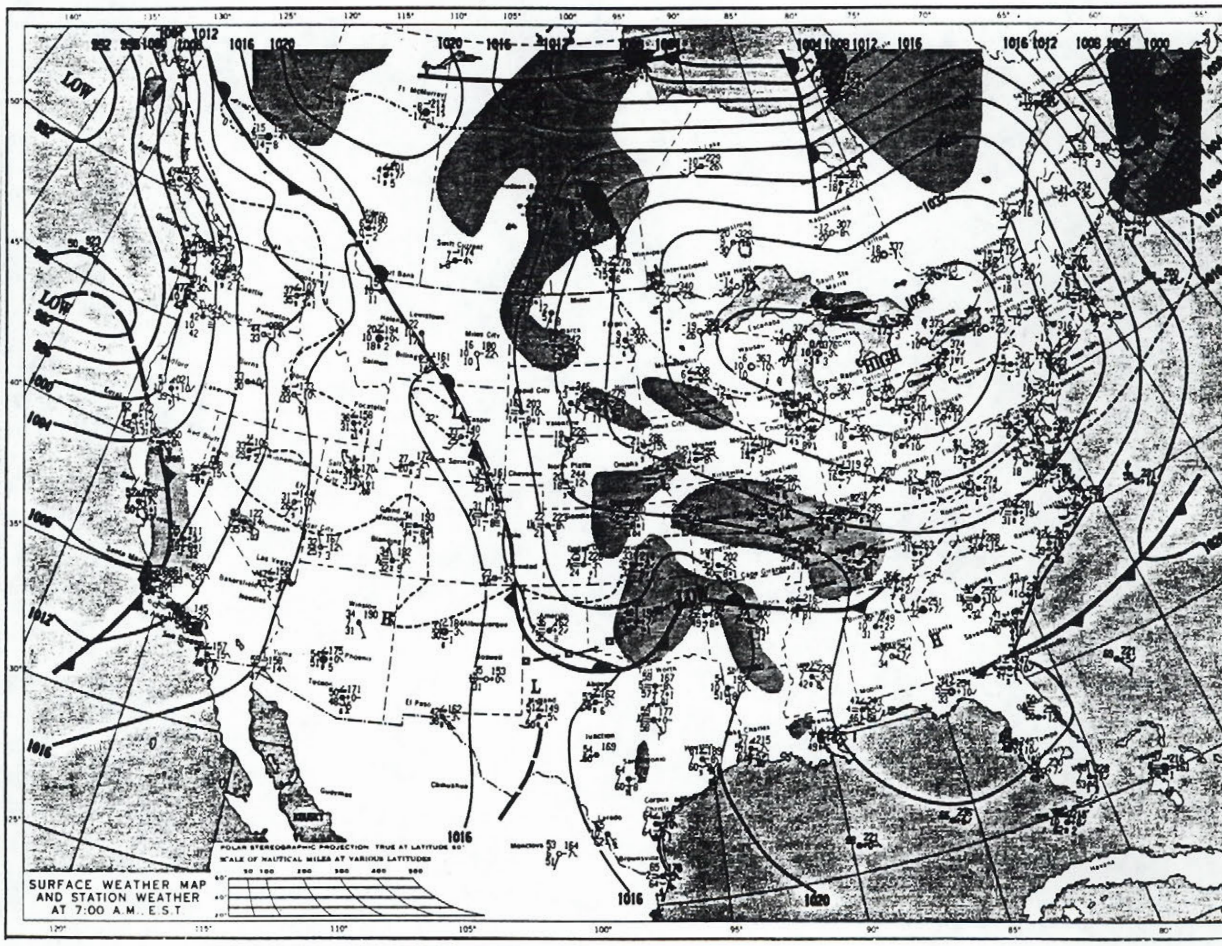


SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M., E.S.T.

TUESDAY, FEBRUARY 11, 1992



WEDNESDAY, FEBRUARY 12, 1992



THURSDAY, FEBRUARY 13, 1992