Very Large Potential Temperature Lapse Rates and Low Turbulence Levels during Spring Thaw on the Prairies

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ABSTRACT

Observations show that two phenomena that are generally considered mutually exclusive occur both night and day during spring thaw over flat cultivated prairies: extremely large potential temperature lapse rates and low levels of atmospheric turbulence. Magnitudes of the large lapse rates routinely exceeded 20°C (100 m)$^{-1}$, whereas levels of turbulence during night and day were at values usually associated with moderately stable and near neutral conditions, respectively. Coexistence of these phenomena occurs during the time of year when a significantly large portion of the prairie is characterized by water and/or ice while the remainder comprises bare soil surfaces. Whereas freezing water is a sensible heat source during the night and melting ice a heat sink during the day, the bare soil acts in a reverse manner being a heat sink during the night and a source during the day. Air moving over the prairie surface is, therefore, subject to, both day and night, an alternating succession of warm and cool surfaces.

Observed boundary layer depths characterized by the very large lapse rates were about 10 m in depth. Calculations based on the first law of thermodynamics show that these depths are consistent with sensible heat fluxes from the prairie surface of about 2 W m^{-2}. Assessments of these small heat fluxes through applications of the energy balance equation show that they are in agreement with the known behavior of melting ice and freezing water during spring thaw.

Extremely large potential temperature lapse rates and low levels of turbulence seem, therefore, to occur because small heat fluxes are being introduced into the air on an interruptible basis. Very large lapse rates persist because the lack of a sustained heat flux does not allow for development of the vigorous turbulence needed for their eradication.

1. Introduction

Leahey et al. (1994, 1995) studied the behavior of atmospheric turbulence observed at 10 m over a flat prairie site near Calgary, Alberta, Canada. They found that medians of standard deviations of wind fluctuations could be predicted from wind speed and static stability. Exceptions were found during spring thaw, when "extremely unstable" atmospheric lapse rates of potential temperature were observed even during nighttime. Accompanying levels of atmospheric turbulence were much lower than would have been expected on the basis of associated wind speeds and static stabilities.

Periods of spring thaw tend to occur in the Calgary region during late March and early April. Snow depths of greater than 3 cm usually do not endure beyond 19 March (Klivokiotis and Thomson 1986). During these periods, the gently undulating cultivated prairie is characterized by alternating patches of bare soil and shallow water bodies. Areas of these different surfaces vary from a few square meters to several hectares depending upon whether the land is flat or rolling, respectively. Observations of one of the authors (M. C. Hansen) and B. Morrow (1995, personal communication), who have farming experience on the prairie, indicate that areas occupied by water may constitute about 30% of the region, whereas the remainder is occupied by soil. Ice melts during the day. About 50% of meltwater is refrozen during the night, resulting in an ice formation with a thickness generally less than 0.5 cm. Water surfaces have very different energy exchange characteristics than soil surfaces because the melting and refreezing of water involves latent heat releases, which are largely absent from areas of bare soil.

There have been several published studies of surface energy budgets and related phenomena associated with snowmelt (e.g., Granger and Male 1978; Male and Granger 1981; McKay and Thurtell 1978; Yamazaki and Kondo 1992; De la Casinère 1974; Price and Dunne 1976; Berris and Harr 1987; Kondo and Yamazaki 1990; Anderson 1968; Kuhn 1987; Föhn 1973; Moore and Owens 1984). All of the studies tended to concentrate on the behavior of large homogenous fields of snow. Results of these studies showed that the transfer of sensible heat was almost always from the atmosphere to the melting (or freezing) surface; behavior that is consistent with stable atmospheres. None of the

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publications concerning homogenous surfaces mention the occurrence of very large temperature lapse rates. The absence of such mention indicates that these gradients are the result of the heterogeneity of the surfaces that characterize the prairie environment during spring thaw.

Although the above cited publications do not concern heterogeneous surfaces, some of their findings may be generally applicable to the small noncontiguous water bodies that exist on the prairies during spring thaw. Two of the most relevant studies are those by Granger and Male (1978) and De la Casinère (1974). The former study was conducted over the Canadian prairies at a latitude of 51.3°N, which is similar to that of the observational site discussed in this paper (51.2°N). The De la Casinère studies were conducted in the French Alps at an elevation of 3550 m and a latitude of about 45°N. Both studies demonstrated that net radiational heat flux, in the absence of air mass changes (i.e., frontal passages), is the major source of energy for the melt of a continuous snow cover. If it is assumed that the heat used in melting is proportional to net radiation, then the studies showed the proportionately coefficient k to be equal to 1.07 and 0.90 for the Canadian prairie and French Alps sites, respectively. Net radiational heat fluxes during daytime at the two locations were about 85 and 110 W m^{-2}, respectively.

The Granger and Male study did not evaluate the portion of meltwater that was refrozen. De la Casinère found that, on average, about 50% of the daily melt was refrozen during the night, forming an ice thickness of about 1 cm. During periods of refreezing, sensible and latent heat exchanges were about 4.4 and −3.6 W m^{-2}, respectively. (The sign convention is such that positive and negative heat fluxes are toward and away from the surface, respectively.) Refreezing was thus accompanied by sensible heat fluxes toward the surface and evaporation heat losses of nearly equal magnitude. Average net radiational heat flux during nighttime was −47 W m^{-2}.

Heat conduction from the melting/freezing water to the soil was estimated to be small (about 1.2 W m^{-2}) and nearly constant during studies conducted over the Canadian prairies. De la Casinère considered it to be of negligible concern for heat exchanges over snow packs in the French Alps.

Purposes of this paper are threefold: to explain how heterogeneous surfaces may result in extremely large lapse rates of potential temperature in the presence of low turbulence, to illustrate the compatibility of these two phenomena and to demonstrate implications of the theory with respect to the behavior of ice melt and refreezing.

2. Theory

a. Energy exchanges at water/ice and soil surfaces

Large regions of the undulating, cultivated prairie are nearly flat with poor water drainage. These regions, during spring thaw, when the wind tends to be southerly, are characterized by alternating surface areas of freezing water (melting ice/snow) and bare soil. These small adjacent surfaces have very different energy budgets, which profoundly affect the structure of temperature, turbulence levels, and surface energy exchanges over the prairies.

During the night, stable air with associated low turbulence levels moves over an area of freezing water in a region of flat, cultivated prairie. This freezing water is a source of sensible heat flux and is maintained at a temperature near 0°C because of the release of latent heat. Heat from the freezing water warms the stable air creating a boundary layer characterized by very large lapse rates. Associated buoyancy forces do not have time to develop to the extent where static stability forces are exceeded, before the air moves over bare soil whose surface temperature, because of radiational heat losses, is less than 0°C. When warm air moves over cold soil, the resulting temperature discontinuity constitutes a shallow and very stable atmospheric temperature configuration that greatly discourages turbulent heat exchanges. Upward buoyancy forces on air parcels, which might normally result in vigorous vertical mixing leading to a reduction in the large lapse rates, are quenched. Strengths of large lapse rates, thus, tend to be maintained over bare soil and to be replenished and strengthened over water/ice areas, whereas levels of turbulence remain virtually unchanged.

During daytime, areas of soil become warm because of shortwave radiation gains, whereas areas of melting ice tend to remain at temperatures near zero because of latent heat requirements. The situation with respect to sensible heat is, thus, reversed from that which occurs during the night, with strengths of lapse rates tending to be replenished over the soil and maintained over the water. In this manner, a boundary layer with very large lapse rates develops within the unstable air as it moves across regions of melting ice during the day. Atmospheric turbulence levels continue to remain virtually unchanged because of the small magnitude of the sensible heat exchanges and the limited time over which buoyancy forces have to develop.

It will be assumed for the above reasons that sensible heat fluxes are upward toward the atmosphere from soil and water surfaces during day and night periods, respectively. Over the same surfaces, these fluxes will be assumed to be negligible during night and day. Thus, the freezing water is the only finite source of turbulent energy transfer during the night, and the bare soil, the only source during the day.

Because the density of water increases from 0° to 4°C (Weast 1973) vertical mixing will tend to maintain temperatures within freezing/melting shallow water bodies uniformly at 0°C and in consequence their heat storages are negligible. With this consideration, the conceptualized scheme for energy exchanges at the water/ice and soil surfaces is as shown in Fig. 1. Here Q_H is the turbulent sensible heat transfer, Q_E is the turbu-

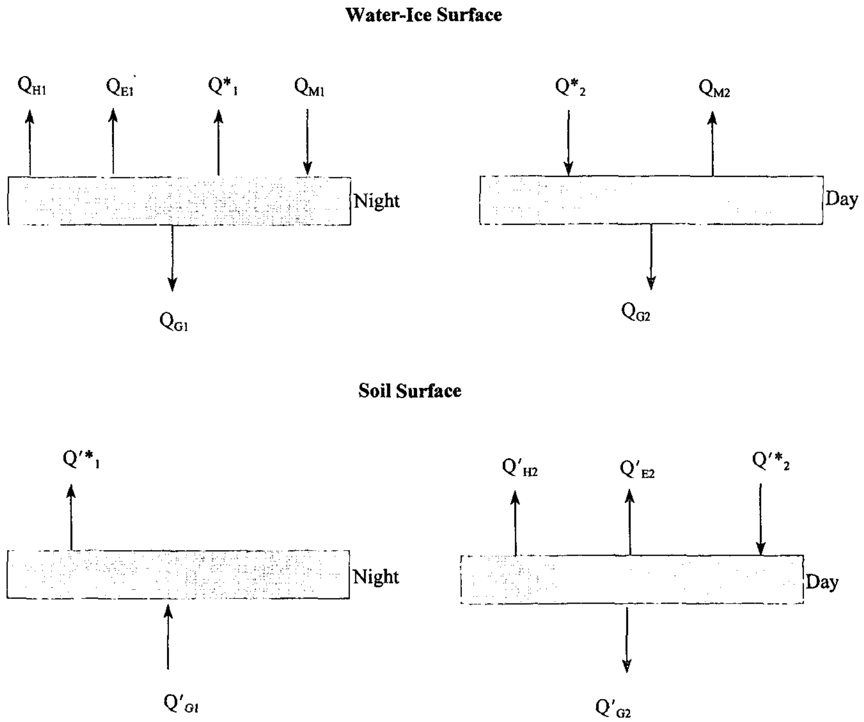

FIG. 1. Hypothesized energy budgets at water/ice and soil surfaces.

lent heat transfer due to evaporation or condensation, Q_G is the transfer of heat across the water–soil interface, Q^* is net radiational heat flux, and Q_M refers to the energy used in fusion. Arrows indicate the direction of the energy exchange with respect to the surface. Subscripts 1 and 2 always refer to night and daytime periods, and primed and unprimed values to soil and water/ice surfaces, respectively. For a given surface, these exchanges, in the absence of precipitation, must balance with

$$Q_M = Q^* + Q_H + Q_E + Q_G. \quad (1)$$

A perusal of Fig. 1 shows that the hypothesized pattern of heat exchanges at the surface is especially simple during day and night over the water/ice and soil surfaces, respectively, when turbulent heat exchanges are negligible. Because of the negligible importance of sensible heat exchange over the soil during the night and over the water/ice surface during the day, values of the lapse rate of potential temperature $(-\Delta\theta/\Delta Z)$ will tend to be regionally constant. This means that there will be one characteristic value for day and another for night.

Illustrations of the hypothesized vertical profiles of potential temperature are presented in Fig. 2. Stable air moves into the freezing prairie region at night where large lapse rates develop over ice/water surfaces. A very shallow stable layer is created as the warm air moves over the cold soil. The presence of this very stable air, which exists near the ground, is shown in Fig. 2 by the dark line above the soil surfaces. As unstable air moves over the region of melting ice during the day a boundary layer with very large lapse rates evolves over the soil and a shallow stable layer over the ice/water surfaces. As indicated, measurements of vertical temperature gradients from the 2- to 10-m levels, for example, should show very strong negative temperature gradients at a given location during both day and night periods. This is because the very stable air layer should not extend upward beyond a few decimeters.

b. Estimates of atmospheric turbulence

The behavior of atmospheric turbulence levels observed during spring thaw may be assessed using equations developed for wind fluctuations by Leahey et al. (hereafter referred to as LHS) (1994, 1995, 1996), from studies conducted at Kathyrn, Alberta, Canada. They showed that median values of half-hourly average standard deviations of wind fluctuations during nonspring thaw periods could be reliably estimated from wind speed and static stability, assumed to be respective surrogates of the mechanical and thermal forces that engender atmospheric turbulence at ground level. Correlation coefficients between predicted and observed variables were frequently in excess of 0.95. Wind speed is commonly employed in most evaluations of atmospheric behavior. Static stability, which is less readily understood, is usually defined as the restoring force to which a unit mass is subjected when

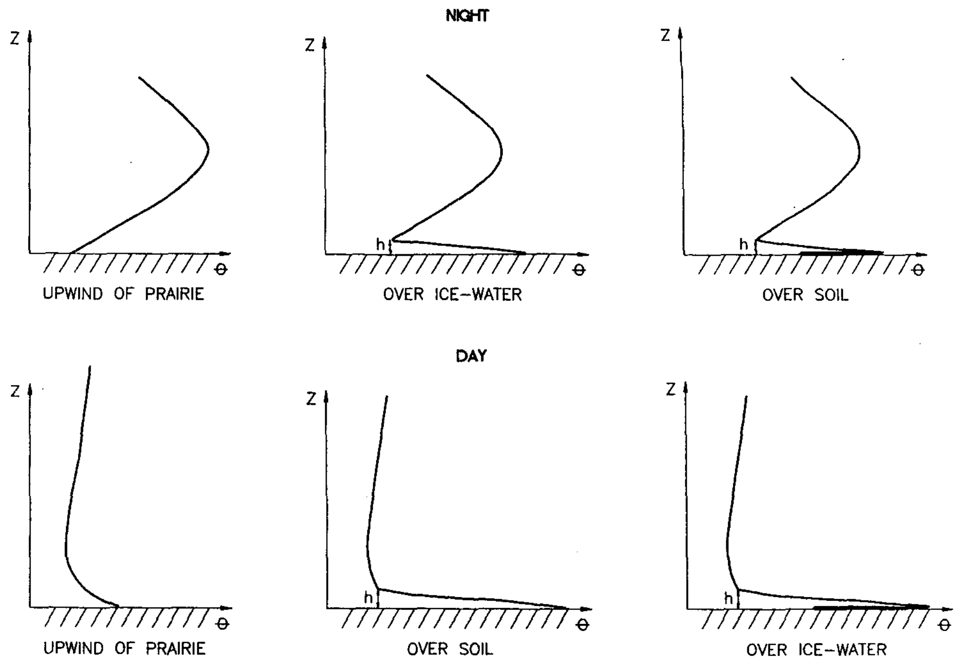

FIG. 2. Hypothesized vertical profiles of potential temperature over the indicated surfaces during night and day.

displaced vertically by a unit distance. The force per unit mass whose potential temperature θ differs by $\Delta\theta$ from the surrounding air being displaced a distance ΔZ is (e.g., Scorer 1958)

$$S = -\frac{1}{\theta} g \frac{\Delta\theta}{\Delta Z},$$

where g is acceleration due to gravity. Static stability has a negative sign because it is in the opposite direction to ΔZ. Atmospheric conditions are defined as stable, neutral, or unstable according to whether the value of S is negative, zero, or positive, respectively.

Static stabilities for stable, neutral, and unstable atmospheres used in the LHS equations for predicting half-hourly average standard deviations of longitudinal, transverse, and vertical wind fluctuations (σ_u, σ_v, σ_w) are normalized by average values observed at the Kathyrn site. Within these equations, primed values of S_n always refer to unstable atmospheric conditions; unprimed values always refer to stable situations; the subscript n always means normalized static stability. Values of S_n and S'_n of 1.0 represent typical stabilities; values of 0.5 and 1.5, respectively, represent slighter and stronger stabilities. Atmospheric turbulence is always predicted to increase with decreasing stability, thus, the greatest levels of atmospheric turbulence are associated with the largest lapse rates.

c. Estimated values for sensible heat fluxes

Sensible heat fluxes into an air column lead to the creation of internal boundary layers that are often characterized by near-adiabatic lapse rates. In the present instance, because of the heterogeneity of the prairie surface, the boundary layer is characterized by a lapse rate that is much greater than the adiabatic lapse rate. The depth of the boundary layer created during the night (see Fig. 2) within a moving column of air by sensible heat fluxes from areas of freezing water may be estimated through application of the first law of thermodynamics (e.g., Leahey and Friend 1971):

$$h^2 = \frac{2\beta}{C_p \rho_1 U_1[(\Delta\theta/\Delta Z)_{01} - (\Delta\theta/\Delta Z)_1]} \int_{x_{01}}^{x_{k1}} Q_{H1}\, dx, \quad (2)$$

where h is the boundary layer depth (m) during nighttime; x_{01} is the distance along the column trajectory at which the region of freezing water begins (m); x_{k1} is the distance along column trajectory (m); β is the fraction of prairie occupied by freezing water surfaces; C_p is the specific heat of air at constant pressure (1003 J kg^{-1} K^{-1}); ρ_1 is the air density (kg m^{-3}); U_1 is the wind speed (m s^{-1}), assumed to be a constant, independent of location; $(\Delta\theta/\Delta Z)_{01}$, $(\Delta\theta/\Delta Z)_1$ are the potential temperature gradients (K m^{-1}) in stable air upwind and over cultivated prairie, respectively. They are assumed to be constant with height; and Q_{H1} is the sensible heat flux (W m^{-2}) from areas of freezing water.

With the assumption that Q_{H1} is constant, Eq. (2) can be integrated and rearranged to give

$$Q_{H1} = \frac{C_p \rho_1 U_1 h_1^2[(\Delta\theta/\Delta Z)_{01} - (\Delta\theta/\Delta Z)_1]}{2\beta(x_{k1} - x_{01})}. \quad (3)$$

An equation similar to Eq. (3) may be derived for the sensible heat flux Q'_{H2} from the bare soil that occurs during daytime:

$$Q'_{H2} = \frac{C_p \rho_2 U_2 h_2^2 [(\Delta\theta/\Delta Z)_{02} - (\Delta\theta/\Delta Z)_2]}{2(1-\beta)(x_{k2} - x_{02})}, \quad (4)$$

where the subscript 2 refers to the daytime values and the prime to energy flux from the soil and x_{02} is the distance along the column trajectory at which the region of melting ice begins (m) and x_{k2} is the downwind distance along the column trajectory (m).

d. Estimated ice melt, water refreezing, and ice thickness

The theory concerning heterogeneous surfaces can be used to estimate values of the energy of fusion used for ice melt and the refreezing of meltwater, through use of the surface energy balance. Application of Eq. (1) to estimate energy used in freezing, Q_{M1}, requires a knowledge of Q_1^*, and Q_{G1}, which in this study have been directly measured, and Q_{H1}, which may be estimated from Eq. (3). Values of Q_{E1} for use in the energy balance equation were approximated from gradient transfer theory developed initially for horizontally homogeneous surfaces. It states that heat flux and evaporation are directly proportional to the vertical gradients of potential temperature and humidity, respectively (e.g., Munn 1966):

$$Q_{H1} = C_p \rho_1 K_H \left(\frac{\Delta\theta}{\Delta Z}\right)$$

$$Q_{E1} = L_v K_w \left(\frac{\Delta\rho_v}{\Delta Z}\right),$$

where L_v is the latent heat of vaporization (2 500 000 J kg^{-1}); $\Delta\rho_v/\Delta Z$ is the humidity gradient between water/ice surface and measurement level, assumed to be constant with height (kg m^{-4}); and K_H, K_w are the exchange coefficients for heat and moisture, respectively (m^2 s^{-1}).

It has been assumed, following the findings of Granger and Male (1978), that $K_w = 0.5K_H$. This assumption is also consistent with the findings of McBean and Miyake (1972), Warhaft (1976), and Verma et al. (1978). It follows that

$$Q_{E1} = \frac{L_v \Delta\rho_v}{2C_p \rho_1 \Delta\theta} Q_{H1},$$

where $\Delta\rho_v$ is the difference in humidity (kg m^{-3}) between water/ice surface and measurement level and $\Delta\theta$ is the difference in potential temperature (K) between water/ice surface and measurement level.

Estimates for the percentage of meltwater that is refrozen R_f may be obtained using the ratio Q_{M1}/Q_{M2}; whereas estimates of the ice thickness associated with the energy released in fusion Q_{M1} are given by the conservation equation

$$D = \frac{100 Q_{M1} t}{\rho_i L_f},$$

where D is the ice thickness (cm), t is the period of freezing (s), ρ_i is the ice density (917 kg m^{-3}), and L_f is the latent heat of fusion (334 000 J kg^{-1}).

3. Description of observational site and instrumentation

Measurements of ambient temperatures, atmospheric turbulence, relative humidity, net radiation flux, and soil heat flux were conducted at a prairie site near Kathyrn, Alberta, about 15 km northeast of Calgary from October 1988 to September 1989 by the Alberta Energy Resources Conservation Board (ERCB). Heights of the topography surrounding the observational site, as well as the location of Calgary, are illustrated in Fig. 3. Flat regular terrain extends outward beyond 100 km from the site in the north, east, and south directions. The Rocky Mountain foothills lie about 35 km to the west. During the early spring, the soil normally cultivated for cereal crops is bare or covered with stubble. A combination of furrows and undulating terrain creates many small areas in which water collects. Climatological temperatures in the Calgary area at the 2-m level during spring thaw, which usually extends from late March to early April, are about −1.7° and 2.4°C for night and day periods, respectively (Klivokiotis and Thompson 1986).

Temperature data were collected using copper-constantan thermocouple junctions at the 2-, 10-, 16-, and 25-m levels of a 25-m tower located during spring thaw in wet ground with generally a water/ice surface. Thermocouple leads were kept at the same length. The sensors were aspirated with R. M. Young motor-aspirated ventilation shields and confirmed within 0.01°C of each other by immersion in an ice-water bath. A Kaijo Denki Co. Ltd. model DAT310 sonic anemometer with the TR61A probe located at the 10-m level was used for all wind measurements. Specifications for the anemometer stipulate a wind accuracy of ±1% with a resolution of 0.005 m s^{-1}. Measurements of relative humidity were obtained using a Phys-Chemical Research Model PC RC-11 relative humidity probe located at the 2-m level. Calibration factors as provided by the manufacturer were accepted and applied to all data. A Qualimetrics pyrradiometer (model 3040A) mounted 1.5 m above the ground at a distance of 10 m from the instrumented meteorological tower was used to measure net radiation flux. Lupolene domes protected the measuring surfaces from wind and moisture. Internal condensation within these domes was prevented by pressurizing them with a continuous stream of nitrogen gas.

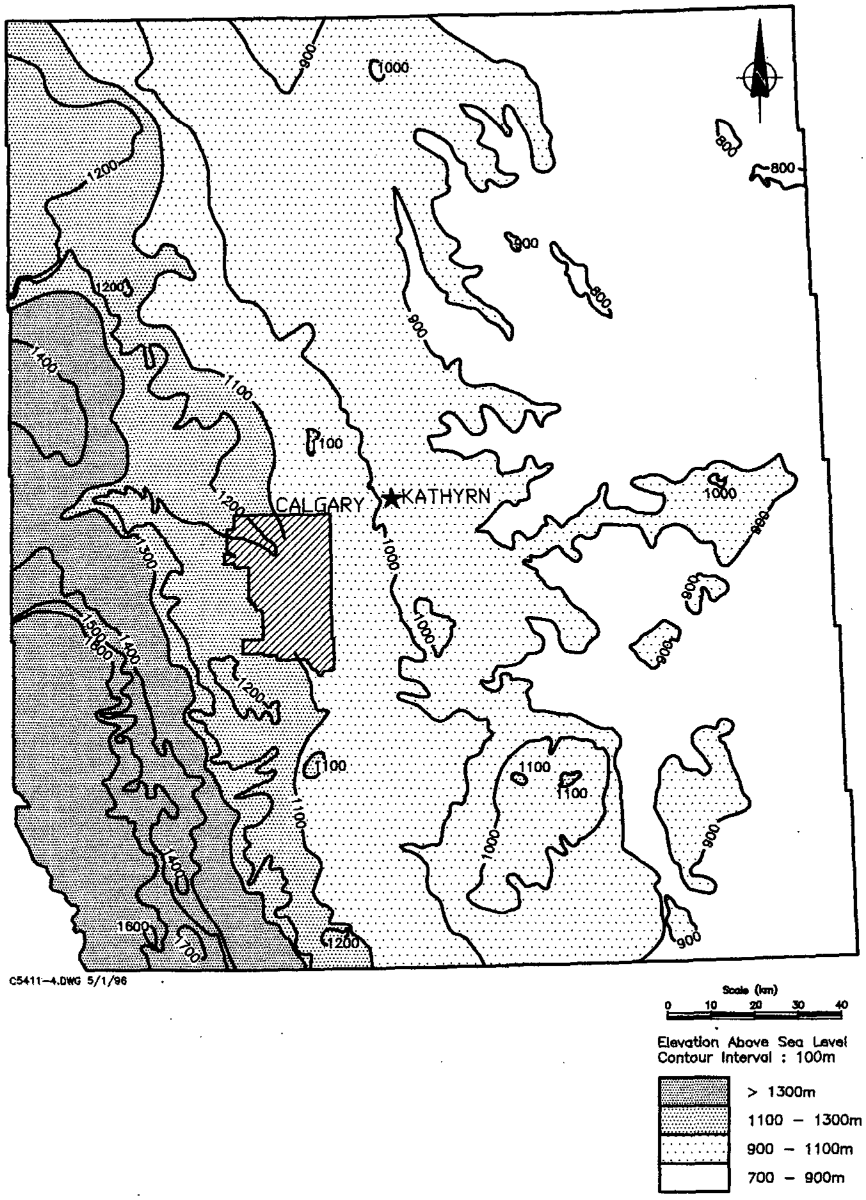

FIG. 3. Schematic map showing elevations (m) of topography surrounding the Kathyrn observation site.

The factor applied to convert instrument output to radiation flux units (W m^{-2}) was obtained using field calibrations. Measurements of soil heat flux were obtained through the use of two soil heat flux plates buried at 10 cm.

The ERCB study was designed and executed to assess risks associated with sour gas (i.e., gas containing H_2S) facilities. The program did not include observations of ice/snow melt or ice thicknesses.

More details of the site instrumentation and data collection procedures may be found elsewhere (ERCB 1990; Leahey et al. 1994).

4. Results

Meteorological data associated with periods of spring thaw were analyzed to determine values of the vertical gradient of potential temperature and atmospheric turbulence associated with the melting and refreezing of water surfaces. Spring thaw periods were primarily defined according to whether they occurred in association with a daily cycle of temperatures from above to below freezing values. Boundaries to the periods were also determined to some degree by the occurrence of large lapse rates of potential temperature.

Table 1. Selected spring thaw episodes.

Episode	Comments
2330 MST 9 March to 0200 MST 12 March 1989	Cold period following rain
1700 MST 24 March to 2330 MST 4 April 1989	Freezing during the night, warming during the day
0000 MST 6 April to 2330 MST 9 April 1989	Freezing during the night, warming during the day
0000 MST 16 April to 2400 MST 16 April 1989	Cold period following rain showers

Table 1 presents the selected periods identified with spring thaw with accompanying comments as to reasons for their selection.

For future narrative convenience, day and nighttime periods during the spring thaw have been identified with periods of net radiation that were positive and negative, respectively. In addition, observed values of net radiation equal to zero were assumed to occur during the night. This mode of dividing the two periods has previously been adopted by De la Casinère (1974).

a. Meteorological phenomena occurring during spring thaw

Figures 4 and 5 present cumulative frequency distributions of half-hourly average vertical potential temperature gradients measured between the 2 and 10 m levels during night and day, respectively, for spring thaw periods identified in Table 1. The figures also present distributions of vertical potential temperature gradients observed during other periods of the year. The total number of half-hourly values upon which the graphs are based is shown in brackets. Very large negative values of the potential temperature gradients associated with spring thaw are immediately obvious. Median values of the potential temperature gradient for night periods during spring thaw and other periods are $-1°$ and $11°C\ (100\ m)^{-1}$, respectively. Comparable values for day periods are $-11°$ and $-1°C\ (100\ m)^{-1}$. While the medians are distinctly different, the extremes are even more so. The largest negative value of the potential temperature gradient observed during a spring thaw night was -120, while during other periods it was only $-4°C\ (100\ m)^{-1}$. During the day, comparable values were about $-100°$ and $-18°C\ (100\ m)^{-1}$, respectively.

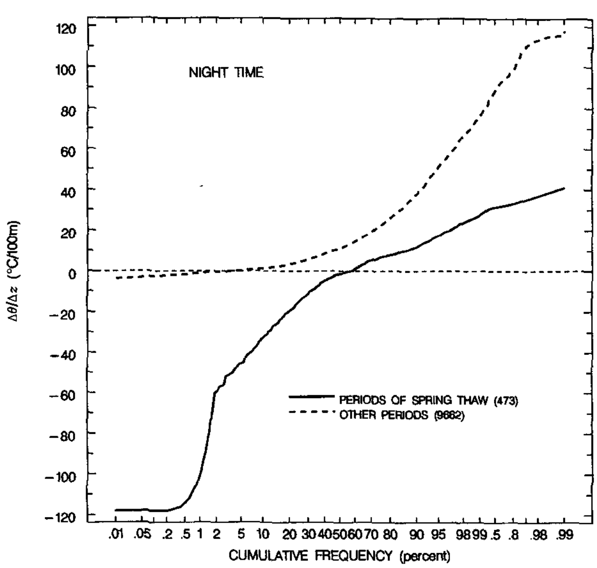

Fig. 4. Cumulative frequency distributions of nighttime $\Delta\theta/\Delta Z$ [$°C\ (100\ m)^{-1}$] values measured between the 2- and 10-m levels during spring thaw and other periods.

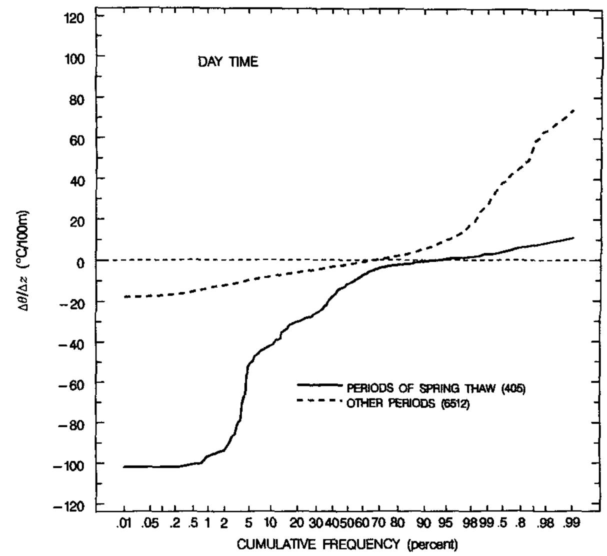

Fig. 5. Cumulative frequency distributions of daytime $\Delta\theta/\Delta Z$ [$°C\ (100\ m)^{-1}$] values measured between the 2- and 10-m levels during spring thaw and other periods.

According to theory, the heterogeneous nature of the flat, cultivated prairie surface should result in large potential temperature lapse rates when air is being advected over areas of melting ice (day) or freezing water (night). It was arbitrarily decided to identify periods of melting and refreezing with values of potential temperature gradients less than $-18°$ and $-4°C\ (100\ m)^{-1}$, respectively. Lapse rates were thus deemed to be always greater than those observed during other times of the year. In this manner, 167 and 190 half-hour intervals were selected for further study of day and night behavior, respectively. This represents about 40% of the episodes identified in Table 1 with spring thaws.

A perusal of potential temperature gradient data identified with freezing water showed that very large lapse rates during the night were limited to about the first 10 m of the atmosphere. Potential temperature gradients between the 10- and 16-m levels were similar to those that occurred in nonspring thaw periods. Thus, during night, lapse rates of greater than $4°C\ (100\ m)^{-1}$

TABLE 2. Median values of meterological data observed during those periods of spring thaw identified with melting or freezing of water as a function of hour of the day. The number of data n upon which the medians are based is also shown.

Hour (MST)	n	Q^* (W m^{-2})	Q_G (W m^{-2})	T (°C)	$\Delta\theta/\Delta Z$ [°C (100 m)$^{-1}$]	RH (%)	Wind dir. (°)	U (m s^{-1})	σ_u (m s^{-1})	σ_v (m s^{-1})	σ_w (m s^{-1})
0000	17	−8.3	−3.0	0.2	−16	91	160	3.8	0.52	0.43	0.22
0100	16	−12.8	−3.6	−1.2	−20	91	205	4.2	0.48	0.46	0.22
0200	17	−7.0	−3.7	−1.3	−26	90	170	4.4	0.51	0.42	0.19
0300	19	−7.8	−2.6	−1.0	−19	90	270	3.9	0.60	0.41	0.22
0400	14	−7.8	−3.7	−2.5	−12	91	265	4.3	0.52	0.35	0.21
0500	21	−15.7	−1.6	−2.6	−16	90	255	3.8	0.45	0.34	0.18
0600	28	−10.0	−3.3	−2.5	−29	90	250	3.2	0.45	0.43	0.18
0700	25	6.4	−2.0	−1.7	−31	83	250	2.9	0.61	0.45	0.21
0800	23	32.8	−3.0	0.9	−30	85	260	2.7	0.61	0.52	0.28
0900	20	68.1	−4.2	1.5	−35	77	260	2.9	0.63	0.49	0.28
1000	20	66.8	−3.9	2.5	−30	61	270	3.5	0.65	0.63	0.28
1100	16	91.8	−5.2	5.3	−29	53	260	3.4	0.71	0.74	0.27
1200	14	100.7	−5.6	5.3	−30	48	180	3.7	0.63	0.52	0.25
1300	12	127.4	−6.1	7.0	−30	46	165	3.6	0.67	0.82	0.28
1400	12	133.0	−6.4	7.5	−28	38	40	3.6	0.61	0.49	0.40
1500	10	82.9	−6.4	7.1	−27	42	55	2.9	0.83	0.54	0.35
1600	9	62.1	−6.4	6.8	−24	44	100	2.1	0.47	0.67	0.21
1700	6	4.0	−5.8	2.3	−25	67	190	2.9	0.39	0.47	0.15
1800	12	−11.8	−5.6	1.4	−16	87	145	3.6	0.49	0.41	0.17
1900	12	−20.8	−5.7	1.1	−16	88	170	4.1	0.48	0.42	0.17
2000	6	−17.3	−5.7	0.1	−18	90	130	3.0	0.39	0.27	0.16
2100	9	−13.3	−5.0	−3.2	−6	89	80	3.2	0.51	0.34	0.15
2200	8	−24.9	−4.7	−2.8	−12	91	80	3.5	0.48	0.35	0.18
2300	11	−8.9	−3.9	−0.3	−25	92	155	3.7	0.50	0.42	0.19

did not occur between the 10- and 16-m levels, unstable gradients between these levels occurred about 10% of the time, and the median gradient in the stable air was about 7°C (100 m)$^{-1}$. Large lapse rates of potential temperature identified with the melting of ice during the day appeared to be similarly restricted to the first 10 m of the atmosphere. Very large lapse rates between the 10 and 16 m levels did not occur, and the median gradient between these two levels were −3° versus −2°C (100 m)$^{-1}$ for nonspring thaw periods.

Median values of meteorological parameters for spring thaw periods identified with the melting of ice or freezing of water are presented as a function of hour of the day in Table 2. Day periods, identified with positive net radiation, extend for 11 h from 0700 to 1700 MST. The remainder of the 24 h makes up the night period. Wind directions tended to be highly variable with average winds from west, south, and east occurring during both the day and night.

Data shown in Table 2 are summarized according to night and day in Table 3. Boundary layer depths are shown as being 10 m for both night and day periods. Values for potential temperature gradients upwind of the region of freezing water/melting ice [i.e., $(\Delta\theta/\Delta Z)_{01}$, $(\Delta\theta/\Delta Z)_{02}$] are night and day medians, respectively, observed at the Kathyrn site during nonspring thaw periods. They are based on the assumption that air upwind of the freezing/melting region will be-

TABLE 3. Average values of meterological parameters identified with the melting of ice or freezing of water.

Night (freezing)		Day (melting)	
Parameter	Value	Parameter	Value
Q_1^* (W m^{-2})	−12.8	Q_2^* (W m^{-2})	70.5
Q_{G1} (W m^{-2})	−4.0	Q_{G2} (W m^{-2})	−5.0
T_1 (°C)	−1.1	T_2 (°C)	4.0
$(\Delta\theta/\Delta Z)_1$ [°C (100 m)$^{-1}$]	−18	$(\Delta\theta/\Delta Z)_2$ [°C (100 m)$^{-1}$]	−29
$(\Delta\theta/\Delta Z)_{01}$ [°C (100 m)$^{-1}$]	10	$(\Delta\theta/\Delta Z)_{02}$ [°C (100 m)$^{-1}$]	−4
$(\mathrm{RH})_1$ (%)	90	$(\mathrm{RH})_2$ (%)	59
Wind direction	180	Wind direction	185
U_1 (m s^{-1})	3.7	U_2 (m s^{-1})	3.1
h_1 (m)	10	h_2 (m)	10
σ_{u1} (m s^{-1})	0.49	σ_{u2} (m s^{-1})	0.62
σ_{v1} (m s^{-1})	0.39	σ_{v2} (m s^{-1})	0.58
σ_{w1} (m s^{-1})	0.19	σ_{w2} (m s^{-1})	0.27

TABLE 4. Estimated values of energy exchange components (Q_{H1}, Q'_{H2}, Q_{E1}, Q_{M1}, Q_{M2}) as a function of β. Values of R_f and D are also shown.

β	Q_{H1} (W m^{-2})	Q'_{H2} (W m^{-2})	Q_{E1} (W m^{-2})	Q_{M1} (W m^{-2})	Q_{M2} (W m^{-2})	D (cm)	R_f (%)
0.2	−4.0	−1.0	−6.0	26.8	−65.5	0.4	41
0.3	−2.6	−1.2	−3.9	23.3	−65.5	0.4	36
0.4	−2.0	−1.4	−3.0	21.8	−65.5	0.3	33

have in the usual fashion. Support for this assumption is found in the fact that temperature gradients above the 10-m boundary layer, are similar to those which normally occur.

A perusal of Table 3 shows that potential temperature lapse rates were somewhat larger during the day than during the night. Average atmospheric temperature occurring during the night in association with refreezing of meltwater was −1.1°C, whereas the average daytime temperature associated with melting of ice was 4°C. Atmospheric turbulence levels as indicated by values of σ_u, σ_v, σ_w were larger during the day. Wind speeds tended to be greater during the night when water was freezing than during the day when ice was melting. Overall average wind directions tended to be southerly during both day and night.

b. *Evaluations of observed turbulence levels*

Average values of potential temperature lapse rates associated with freezing water (nighttime) and melting (daytime) cycles of the spring thaw were very large, being 18° and 29°C (100 m)$^{-1}$, respectively. These correspond to values of static stabilities normalized for unstable atmospheres (S'_n) of 4.5 and 7.3, respectively.

Calculations using the lhs equations showed that the average values of horizontal and vertical turbulence (σ_u, σ_v, σ_w) observed during periods of freezing water were only about 25% of those that would have been expected for the associated static stabilities and wind speeds. Further calculations using the equations showed that the observed turbulence was more at the level usually identified with moderately stable atmospheric conditions ($S_n = 1.0$).

Values of atmospheric turbulence observed during ice melt were similarly found to be much less than the values corresponding to the very large lapse rates. Horizontal and vertical turbulence were only at levels normally associated with slightly unstable ($S'_n = 0.5$) and slightly stable ($S_n = 0.5$) atmospheric conditions, respectively.

c. *Estimated values of energies used to establish boundary layer depths, and for the melting and freezing processes*

Lengths of time over which ice froze or thawed were assumed to coincide with the night and day periods obtained from Table 2. This means that air columns travel on average about 6.5 and 5.5 h during freezing and thawing periods, respectively, before reaching the Kathryn observational site. Associated travel distances with mean wind speeds of 3.7 and 3.1 m s^{-1} as shown in Table 3 are about 85 and 60 km, respectively. These values for $(x_{k1} - x_{01})$ and $(x_{k2} - x_{02})$ were used in Eqs. (3) and (4) together with potential temperature gradients and wind speeds shown in Table 3 to estimate sensible heat fluxes associated with development of the 10-m boundary layers.

Values of $\Delta\theta$ and $\Delta\rho_v$ used in calculating Q_{E1} were obtained under the assumption that ambient temperatures at 2 m and associated gradient were −1.1° and −18°C (100 m)$^{-1}$, respectively. Air at the derived ice surface temperature of −0.74°C was assumed to be saturated, while that at 2 m was assumed to be at a relative humidity of 90% as indicated in Table 3.

Estimates of latent heat exchanges due to refreezing and melting (Q_{M1}, Q_{M2}) were obtained through use of the energy balance equation [Eq. (1)] with the assumption that values of Q^*, and Q_G are as given in Table 3.

Table 4 presents estimates of turbulent energy exchanges and heats of fusion associated with phase changes as functions of β. It also presents associated values of ice thickness (D) and the fraction of meltwater that is refrozen during the night (R_f). Estimated values of the turbulent energies are small with greater sensible heat releases predicted for the freezing water than for the soil surfaces. Predicted values for D and R_f are insensitive to the assumed β values.

5. Conclusions

Data presented in Table 4 indicate that the amount of refrozen meltwater should tend to be less than 50% and associated ice thickness less than 0.5 cm. This conclusion, which is supported by anecdotal evidence, supplied by one of the authors with prairie farming experience (M. C. Hansen) and a fellow scientist with a similar background (B. Morrow, 1995 personal communication) is not sensitive to the portion of the cultivated prairie assumed to be occupied by ice/water surfaces (β). Values for β of about 0.3 correspond to anecdotal evidence. They would also fulfill the theoretical requirement that an appreciable portion of the prairie be occupied by freezing/melting water surfaces. This requirement ensures that buoyancy forces engendered by a heating surface do not have time to develop before they are quenched by passage of air over a cooler surface. Table 4 also shows that the amount of heat energy used during the day for ice melt is 65.5 W m^{-2}. This value is 0.93 times the net radiation indicating that this heat budget component must account for the overwhelming portion of ice melt. Such a conclusion is confirmed by study results reported in the literature.

It has been demonstrated that extremely large lapse rates of potential temperature may exist in the presence of low turbulence levels during spring thaw when there is a small interruptible flux of sensible heat into the air. The presence of the small heat flux ($\sim$2 W m^{-2}) is consistent with the known behavior of melting ice and freezing water.

The situation is reminiscent of occasions whereby solvents may be induced by gradual cooling to contain amounts of solute well in excess of the equilibrium level associated with saturation. In this instance, stable air seems to be induced by gradual warming to accept a lapse rate of potential temperature that is well in excess of its equilibrium turbulence level. The static stability indicated by the lapse rate is thus not authenticated by the associated degree of wind fluctuations.

The unusual atmospheric conditions that exist during spring thaw could provide a valuable environment for studying the manner in which buoyancy and static stability forces obey physical laws. Research efforts could be especially fruitful because of the wide range of lapse rates, small mixing layers, relatively low turbulence, restricted temperature ranges, and weak winds which typify the spring thaw.

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