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Abstract: Ice wedges on northern Richards Island, Northwest Territories, and along the Yukon Territory coastlands, have responded to increased thaw depths. Observations made in 1999 are compared to those last made in these areas in 1975 and 1984, respectively. Climate data indicate that air temperatures in these areas have been warmer than average since 1978 and that warming in 1998 was an extreme event. Increased thaw in response to this warming has caused a decrease in the number of secondary and tertiary ice wedges, and is attributed to thaw truncation. Depths to the tops of ice wedges on Richards Island have increased, whereas depths have decreased on the Yukon Territory coastlands due to thaw consolidation. Thaw-tube observations indicate that 1998 thaw depths were the greatest since 1991 across the northern Mackenzie Delta region, with increases of as much as 21 cm.

Résumé : Les fentes de glace dans le nord de l'île Richards (Territoires du Nord-Ouest) et le long des terrains côtiers du Territoire du Yukon, ont réagi à l'accroissement de la profondeur de dégel. On compare les observations faites en 1999 avec celles faites dans les mêmes régions en 1975 et en 1984, respectivement. Les données climatiques indiquent que depuis 1978, la température de l'air dans ces régions a été plus élevée que la moyenne et qu'en 1998, le réchauffement a été un événement extrême. Suite à ce réchauffement, un dégel plus profond a causé une diminution du nombre de fentes de glace secondaires et tertiaires et est attribuable à la troncature par le dégel. La profondeur jusqu'au sommet des fentes de glace a augmenté dans l'île Richards alors qu'elle a diminué le long des terrains côtiers du Territoire du Yukon en raison de la consolidation due au dégel. Les observations dans les tubes de dégel ont indiqué qu'en 1998, la profondeur de pénétration du dégel a été la plus grande depuis 1991 dans le nord du delta du Mackenzie, avec des augmentations allant jusqu'à 21 cm.

INTRODUCTION

The Mackenzie Delta and Yukon coast region is an ice-rich, permafrost landscape underlain by thick sequences of unconsolidated Quaternary sediments. Ground ice in the form of pore ice, ice wedges, segregated ice, and pingos is abundant. In addition, extensive bodies of segregated and buried ice are also common (Mackay, 1972; French and Harry, 1990; Mackay and Dallimore, 1992). Specific geomorphic processes related to the occurrence of ice are active in this region including enhanced rates of coastal erosion, thermokarst, active-layer detachments, retrogressive thaw flowslides, and deep-seated permafrost creep (Dallimore et al., 1996a, b). These processes can be sensitive to climatic forcings such as changes in surface air temperature that, in turn, affect the ground thermal and physical regimes within permafrost (e.g. Mackay, 1995; Dallimore et al., 1996b). The active layer, conventionally defined as the depth of seasonal penetration of the 0°C isotherm (Muller, 1947), is particularly sensitive to changes in surface air temperature (Mackay 1975; 1976; Burn, 1998b). Active-layer thinning (attenuation) resulting from surface cooling is accompanied by the upward aggradation of permafrost, whereas greater thaw penetration due to increased surface temperatures results in thawing of the top of permafrost (Mackay, 1972, 1976).

Ice wedges grow in response to snowmelt infill of thermal contraction cracks in permafrost (Mackay, 1974). They are truncated at their tops by the active layer. Where active- layer attenuation results in upward aggradation of permafrost, actively cracking primary ice wedges will develop secondary ice wedges whose tops are at the base of the new active layer. Further attenuation and upward growth will result in tertiary ice wedges and so on, arranged en échelon (e.g. Dostovalov and Popov, 1963). These relationships allow inferences to be made about active-layer changes due to surface- and ground-temperature variations, particularly cooling (e.g. Mackay, 1975, 1976; Harry et al., 1985).

Ground temperatures and modern air-temperature records compiled throughout the Mackenzie River valley and Beaufort Sea coast area show that annual average temperatures likely increased by about 3°C during a late 1800s warming period and decreased by about 2°C from 1940 to the early 1970s (Mackay, 1976). It is estimated that the 3°C warming resulted in increased thaw penetration from 20 to 50 per cent and may have resulted in many ice wedges becoming dormant (Mackay, 1975). Subsequent cooling caused rejuvenation of ice wedges and the development of secondary and tertiary wedges (Mackay, 1976).

In 1998, very strong El Niño conditions resulted in the warmest year on record in Canada, with the national average air temperature 1.5°C higher than in any previous year during

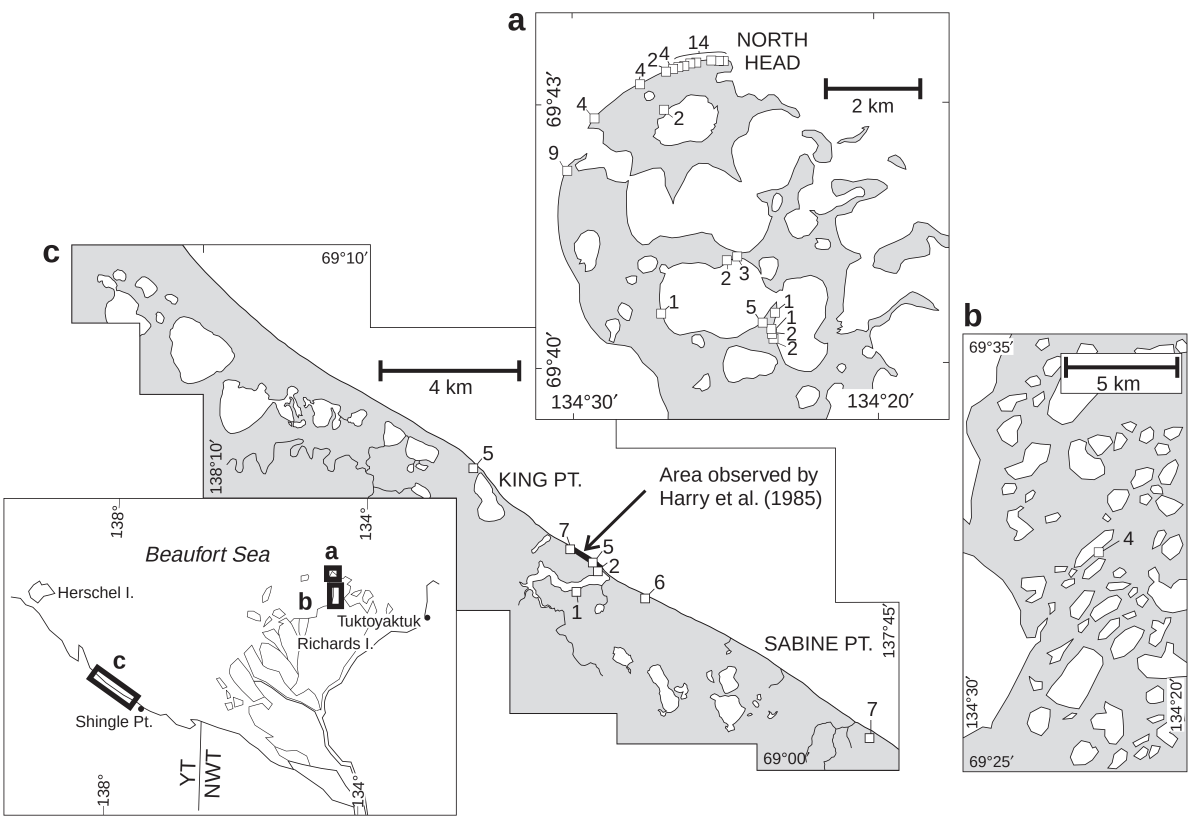

Figure 1. *Study sites on Richards Island and Yukon coast:* ***a)*** *North Head;* ***b)*** *southern section of North Point; and* ***c)*** *Yukon coast. Squares indicate locations of retrogressive thaw flowslides and corresponding numbers refer to the number of ice wedges examined.*

the instrumental record (Environment Canada, 1999). In the Mackenzie valley district of western Arctic Canada, temperatures were as much as 6°C higher than average. These unusually high temperatures in 1998 prompted the Geological Survey of Canada to investigate the short-term response of permafrost to this warming, by comparing ice-wedge characteristics from Richards Island and the Yukon coast with those from previous studies (Fig. 1). Field observations from active-layer monitoring in the Richards Island and Tuktoyaktuk Peninsula area (Nixon, 1998) and historical trends in air temperatures were also interpreted relative to data from 1998.

BACKGROUND AND METHODS

Temperature records

Monthly air-temperature records were obtained from Atmospheric Environment Services, Environment Canada, for 1957 to 1999 at Shingle Point, Yukon Territory, and for 1958 to 1993 and 1996 to 1999 at Tuktoyaktuk, Northwest Territories. Annual averages for both stations were calculated where data for all months were available. For Tuktoyaktuk, where a few individual monthly values were missing, the missing values were replaced by historic average monthly values. Five such replacements were made. At Shingle Point, only one month of data (December 1993) was replaced in this way, as monthly observations were less complete and substitutions were not deemed acceptable.

Active-layer monitoring

The definition of the active layer, as stated by Muller (1947), is based on temperature. Since this parameter is often difficult to measure in the field, the active layer can be more easily defined and measured if it is considered as the thickness of ground that thaws annually (National Research Council, 1988; Burn, 1998a). Using a modified version of a frost tube developed by Mackay (1973), sixty sites installed between 1990 and 1994 throughout the Mackenzie valley and Delta region record maximum annual thaw penetration and maximum heave and subsidence at the ground surface (Nixon, 1998; Nixon et al., 1995). In the Richards Island and Tuktoyaktuk areas, thaw-penetration and ground-surface subsidence data recorded since installation are compared with those from 1998 to determine whether active layers have responded to recent warming events.

Ice-wedge observations

Mackay (1976) reports ice-wedge characteristics and depths to primary, secondary, and tertiary ice wedges recorded in the Richards Island and Tuktoyaktuk areas in summer 1975. These observations reflect a post-1950s cooling trend accompanied by active-layer attenuation of between 10 and 40 per cent (Mackay, 1976). In a similar study on the Yukon coast in 1984, observations also indicate active-layer attenuation of between 10 and 70 per cent, although reported depths to the tops of ice wedges were typically 10 cm greater than those observed in the Richards Island and Tuktoyaktuk areas (Harry et al., 1985).

During the 1999 field season, the tops of ice wedges were examined to determine whether they had changed since 1975 and 1984. Field measurements were made from July 8 to18 along the Yukon coast and from July 19 to August 3 on northern Richards Island. Depths to the tops of primary, secondary, or tertiary wedges were measured and other evidence of recent activity or thawing was noted. In total, 93 ice wedges were examined, 33 of them along the Yukon coast and 60 on northern Richards Island (Fig. 1). As thaw depths had not reached maximums during the 1999 season, it was possible to note evidence of previous winter cracking and thaw truncations attributed to 1998 or previous years.

The ice wedges examined were exposed by ongoing coastal erosion or retrogressive thaw-flowslide activity. Only actively eroding exposures with maximum shoreward headwall extent were examined to ensure that ice wedges were unaffected by previous exposure. In this manner, a sample of the total population of ice wedges was obtained. Samples from the Yukon coast and Richards Island areas were compared with those obtained in previous years by Harry et al. (1985) and Mackay (1976). Harry et al. (1985) examined approximately 30 modern ice wedges exposed in a single large retrogressive thaw flowslide near King Point, Yukon Territory. In the present study, 33 modern ice wedges were observed in same local area, 12 from the same large flowslide. Observations by Mackay (1976) were made from a larger area, including coastal Richards Island, Garry Island, Hooper Island, Pelly Island, and along the coast 5 to 20 km southwest of Tuktoyaktuk. By comparison, our observations in this region were restricted to ice wedges on northern Richards Island.

RESULTS

Air temperatures

Average annual air temperatures reported at Tuktoyaktuk and Shingle Point between 1958 and 1998 show that 1998 was the warmest year on record (Fig. 2). Although a considerable amount of data are missing from Shingle Point, the data indicate that year-to-year trends at the two locations are similar. Although average annual temperatures seem to show a warming trend over the last four decades, the data show no simple, statistically significant trend. Nevertheless, the temperature data do appear to be well divided into two periods, before and after about 1978. For example, all years in which temperatures fall below 1σ of the annual average are prior to 1978 and all years in which temperatures exceed 1σ of the annual average are after 1978. Monthly data for Tuktoyaktuk (not shown) suggest that this difference may be attributed mostly to warmer winter (December, January, and February) temperatures after 1978. However, any overall change in mean annual temperatures since 1978 is small. What is most notable, however, is that 1998 was more than 4.5°C warmer than the historic average of -10.5°C at Tuktoyaktuk. Statistically, this is

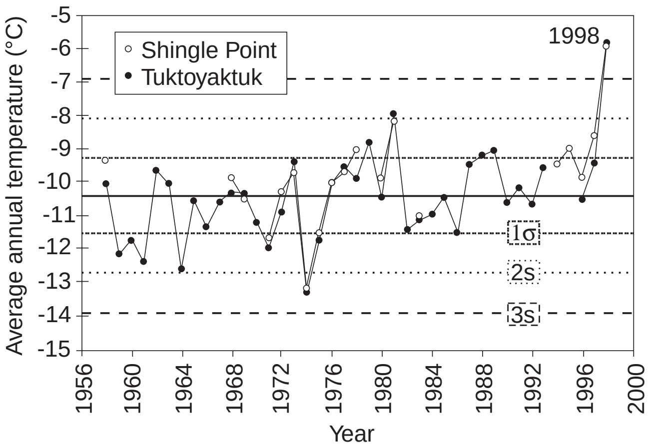

Figure 2. Average annual air temperatures for Tuktoyaktuk, Northwest Territories, and Shingle Point, Yukon Territory. Also depicted is the mean (-10.4°C) and the first, second, and third standard deviations for Tuktoyaktuk. Data from Atmospheric Environment Services, Environment Canada.

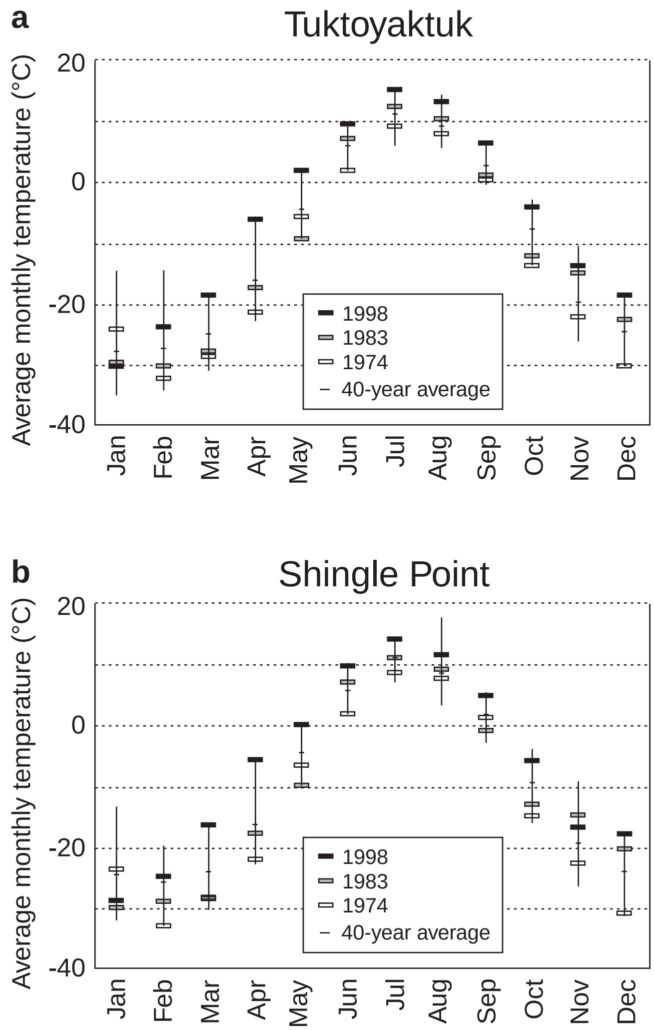

***Figure 3.** Comparison of average monthly air temperatures for Tuktoyaktuk, Northwest Territories, and Shingle Point, Yukon Territory for 1998, 1983, and 1974, as well as the 40-year average. Vertical bars indicate the range in monthly temperatures reported between 1958 and 1998. Data from Atmospheric Environment Services, Environment Canada.*

the only year to fall well outside 3σ, identifying it as an extreme event. In addition to being the warmest year overall, 1998 was warmer than the 40-year average during every month other than January and was particularly warm from March through to July (Fig. 3).

Thaw depth and monitoring of ground subsidence

Maximum annual thaw depths recorded at ten sites in the Richards Island and Tuktoyaktuk areas are shown in Figure 4. These values represent thaw penetration relative to a stable standard reference point, independent of the ground surface, and are not active-layer thicknesses. The use of thaw-penetration data for comparisons of interannual thaw eliminates local complexities associated with ground-ice melting and soil compaction. In general, thaw-penetration data show an increasing trend between 1991 and 1998. This trend corresponds well with average annual air temperatures observed during the 1990s (Fig. 2) and with summer (June, July, August) temperatures (not shown). For example, average annual temperatures were cooler in 1996 than in 1995 and, except for one site east of Tuktoyaktuk, thaw depths in the region were less in 1996 than in 1995. Thaw penetration in 1998 exceeded that of previous years at all sites. Maximum thaw penetration in 1998 was, on average, about 12 cm deeper than previous maximums and as much as 21 cm deeper at site 6 (Fig. 4a). Over the monitored period, thaw penetration in 1998 was 12 to 23 cm (average of 19 cm) deeper than in 1991 or 1992.

Ground-level heights recorded at the time of maximum thaw penetration indicate that subsidence accompanied the increased thaw depths between 1991 and 1998 (Fig. 4c). Since melting of ground ice and consolidation of enclosing sediments and organic material causes thaw settlement, increased thaw penetration is generally accompanied by increased subsidence. This amount of subsidence is highly dependent upon the nature of the substrate and the volume of near-surface ice. Ground-surface subsidence in 1998 exceeded that in all previous years. Ground subsidence ranged from 5 to 25 cm in 1998 (relative to the first year of monitoring) and exceeded previous maximums by 1 to 7 cm.

Given the similarity in trends between the thaw-tube observations and the average annual temperature data, the most likely reason for the increased thaw depths and ground subsidence was response to the warm air temperatures experienced throughout the winter, spring, and summer of 1998. Furthermore, given the similarity in temperatures between Tuktoyaktuk and Shingle Point, it is likely that the Yukon coast experienced maximum thaw depths as well. If the monitored sites represent a reasonable sample of the variability of active-layer development, then it can be expected that thaw depth and subsidence reached a maximum in 1998 across the region.

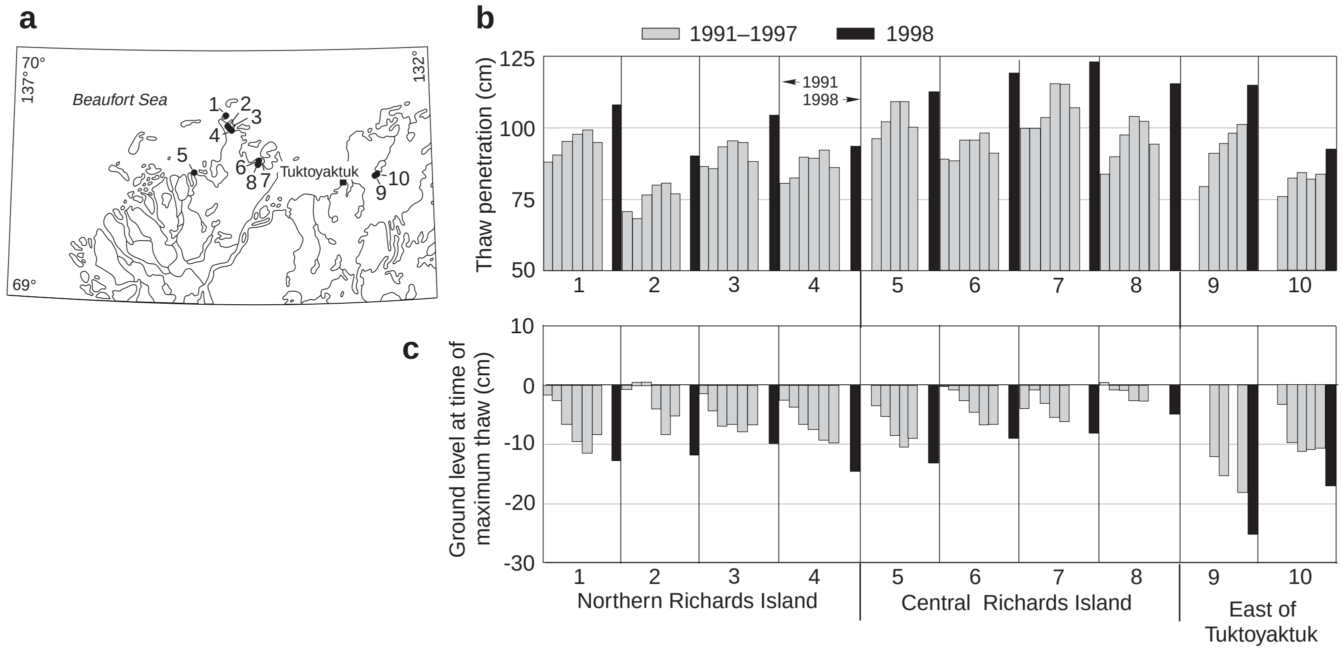

Figure 4. *Thaw-depth monitoring in the Richards Island and Tuktoyaktuk areas:* ***a)*** *locations of thaw tubes;* ***b)*** *1998 thaw penetration compared to previous years since 1991;* ***c)*** *ground levels at the time of maximum thaw, relative to the first year of monitoring. Data from 1997 is missing at most sites because of the rapid progression of thaw in 1998.*

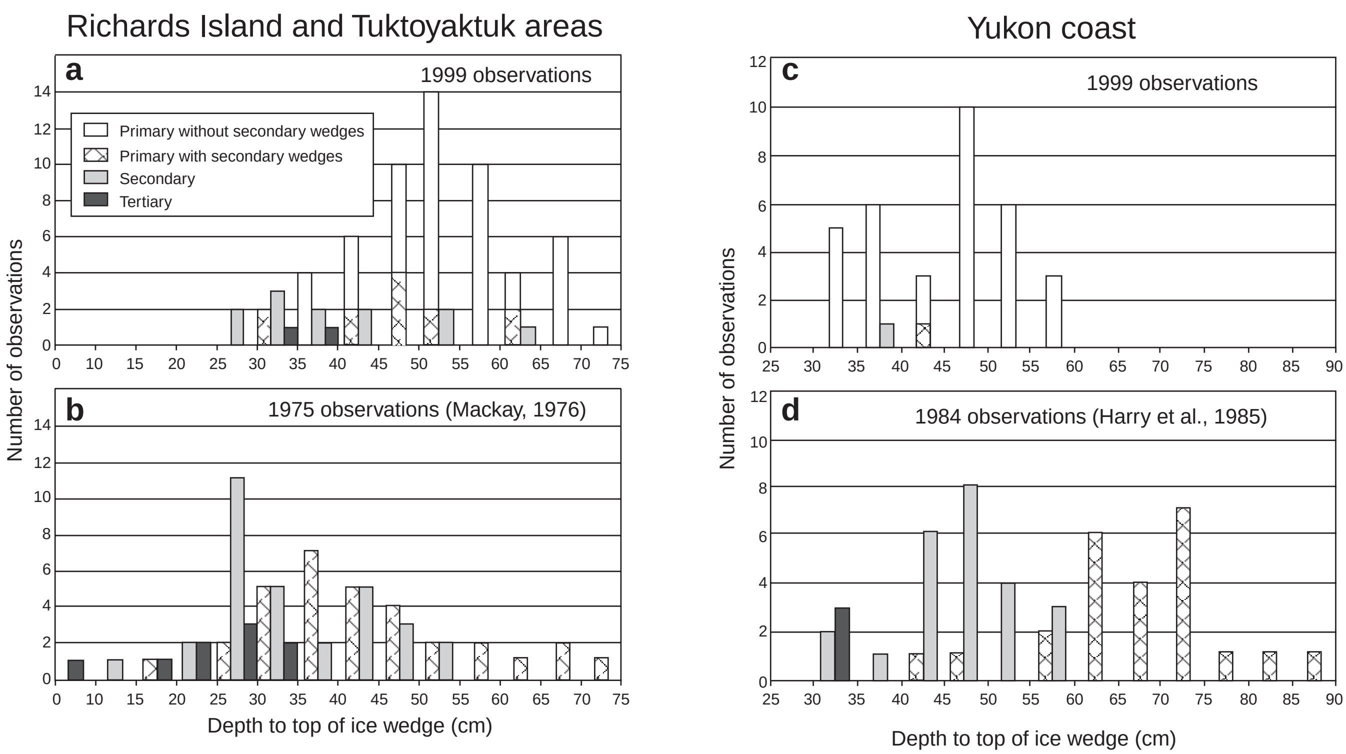

Figure 5. *Depths to top of ice wedges grouped by primary, secondary or tertiary ice wedges:* ***a)*** *northern Richards Island;* ***b)*** *Richards Island and Tuktoyaktuk areas (Mackay 1976);* ***c)*** *Yukon coast and the King Point area; and* ***d)*** *Yukon coast and King Point area (Harry et al., 1985). Note that primary ice wedges reported by Mackay (1976) and Harry et al. (1985) are only those that also contained secondary wedges, whereas a) and c) show primary ice wedges, with or without secondary wedges.*

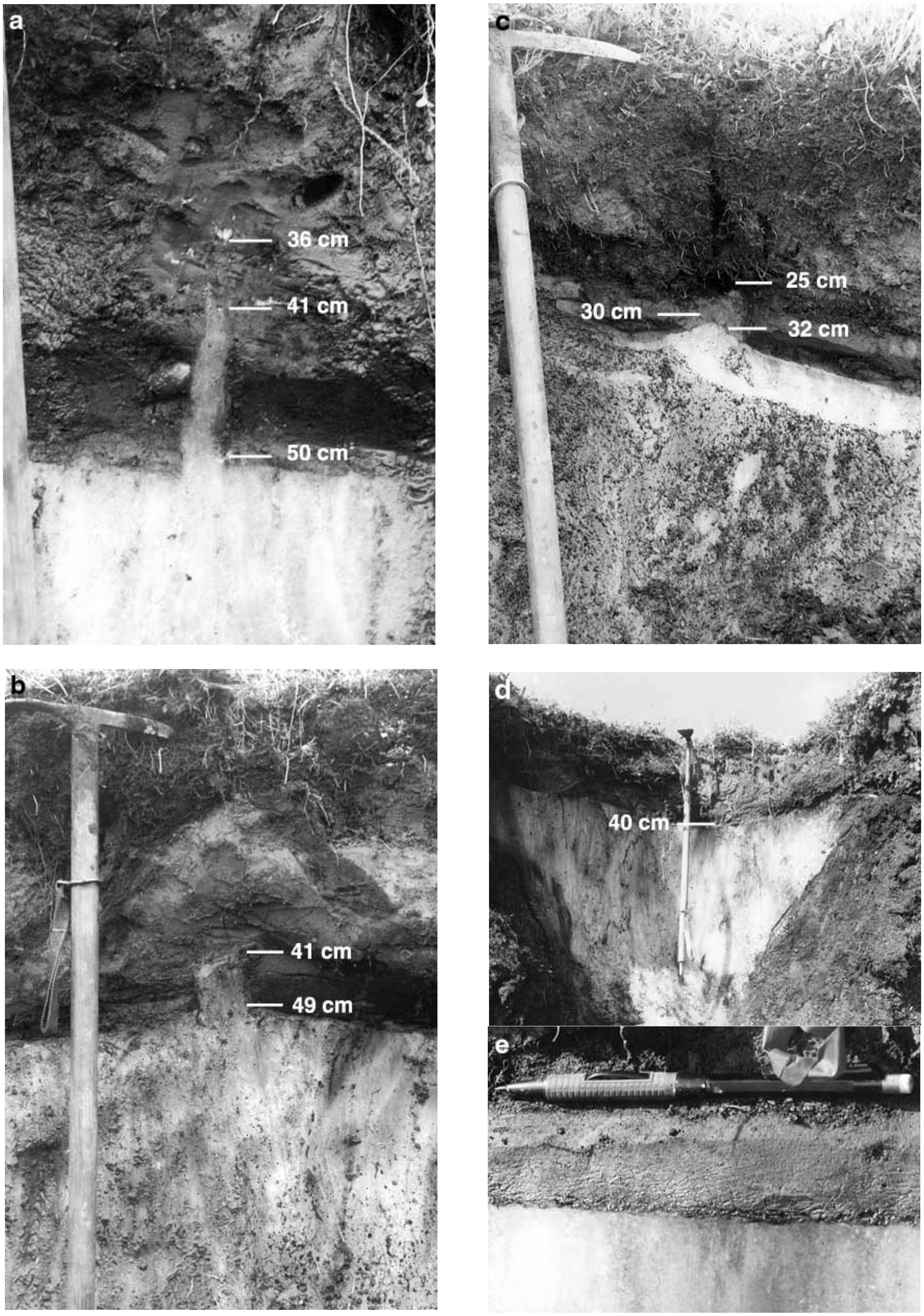

Figure 6. *Photographs of the tops of ice wedges observed on Northern Richards Island and the Yukon coast in July 1999.* ***a)*** *Primary and secondary ice wedges with recent (tertiary) cracking at on northern Richards Island with depths to tops of wedges.* ***b)*** *Ice wedge at North Head with primary and secondary growth. The top of the secondary wedge has been abruptly truncated by thawing.* ***c)*** *Ice wedge at North Head with primary wedge at a depth of 32 cm and a residual secondary wedge at 30 cm. Ice overlying the residual wedge is pool ice, indicating refreezing of water above the wedge.* ***d)*** *Ice wedge with overlying trough along the Yukon coast.* ***e)*** *Modern roots in contact with the top of the ice wedge.*

Ice-wedge observations

Northern Richards Island

In 1975, 26 per cent of ice wedges (including buried, inactive ice wedges) in the Richards Island and Tuktoyaktuk regions contained secondary or tertiary wedges (Mackay, 1976). By comparison, in 1999 this proportion was somewhat less (20 per cent). Although Mackay (1976) only reports data for primary ice wedges that also contained secondary or tertiary wedges, the depth from the ground surface to the top of the wedges ranged from approximately 20 to 75 cm for primary wedges, from 10 to 51 cm for secondary wedges, and from 12 to 54 cm for tertiary wedges (Fig. 5b). Of the 60 ice wedges examined on northern Richards Island in 1999 (Fig. 1a, b), twelve contained secondary ice wedges and two of these contained tertiary wedges (Fig. 5a), some with evidence of recent cracking (Fig. 6a). In 1999, the tops of the primary wedges were from about 35 to 75 cm below the surface, those of secondary wedges, from 25 to 65 cm, and those of tertiary wedges, from 35 to 40 cm. In reviewing these data, the most significant differences are in the minimum depths to the tops of the secondary and tertiary wedges. In 1975, Mackay (1976) observed that 50 per cent of the secondary and tertiary wedges were at a depth of 30 cm or less, with half of these less than 25 cm below the surface. By comparison, in 1999 only two secondary wedges were found at a depth of 25 to 30 cm and none were found at a depth of less than 25 cm.

Although our data are only for the northern Richards Island area, they suggest that the tops of secondary or tertiary ice wedges in this area may have been truncated by thaw to a depth of as much as 30 cm. In addition, most secondary wedges lacked fresh cracks or veinlets and had abrupt tops, suggesting thaw truncation without recent reactivation (Fig. 6b). Other secondary ice wedges were overlain by pool ice, formed by freezing of subsurface meltwater (Mackay, 1986), suggesting that thaw of secondary and/or tertiary wedges had resulted in meltwater refreezing along ice-wedge tops (Fig. 6c). In other cases, open cavities were observed. Although thaw depths may have reached the tops of primary wedges in a few locations, there was no regional evidence of thawing of the tops of primary wedges in the northern Richards Island area. Consequently, the impact of increased thaw depths in 1998 may be mostly restricted to partial or nearly complete thawing of secondary and tertiary wedges. Although some ground settlement above the ice wedges has likely occurred in association with thawing, subsidence is not readily evident in comparisons of 1975 and 1999 ice-wedge observations.

Yukon coast

In 1984, 55 per cent (24 of 40) of modern ice wedges (i.e. those with tops within 90 cm of the surface) contained secondary wedges and 15 per cent of these contained tertiary wedges (Harry et al., 1985). By comparison, of the 33 modern ice wedges examined along the Yukon coast in 1999 (Fig. 1c), only one contained a secondary wedge and this secondary wedge did not contain a tertiary wedge. In 1984, depths to the tops of primary wedges (both modern, single-stage wedges and primary wedges with secondary wedges) ranged from 40 to 90 cm (Fig. 5d; Harry et al., 1985, Fig. 14.7), depths to the top of secondary wedges ranged from 30 and 60 cm, and tertiary wedges occurred at a depth of about 30 cm. By comparison, in 1999, depths to the tops of primary wedges ranged from 30 to 60 cm and the secondary wedge was at a depth of 41 cm (Fig. 5c). These observations indicate that thaw truncation of ice wedges has occurred and that this has also been accompanied by thaw settlement above ice wedges. The difference in the depths to the tops of the primary wedges suggests that a minimum of 10 cm of ground settlement has accompanied thawing in this area. Furthermore, as the majority of depths to tops of primary wedges were within the range of 55 to 75 cm in 1984 (Fig. 5d), this suggests that as much as 20 cm of ground settlement may have occurred between then and 1999.

Evidence of thaw settlement was in the form of overdeepened troughs above ice wedges (Fig. 6d). Evidence indicating that the ground had thawed to the tops of the ice wedges came from observations of actively growing roots extending horizontally along the tops of the ice wedges (Fig. 6e). Seasonal thawing within the active layer has permitted roots to grow vertically to the tops of the wedges and horizontally along the limit of thaw truncation.

DISCUSSION AND CONCLUSIONS

Air temperatures recorded over the last 40 years (Fig. 2) may be placed in the context of earlier observations that a cooling trend, with as much as a 2°C decline in mean annual air temperature, occurred in the western Arctic after the late 1940s or 1950s (Mackay, 1975, 1976; Harry et al., 1985). Temperatures at Tuktoyaktuk and Shingle Point suggest that cooling was probably reflected in air temperatures through to about 1978, with no continuation of this cooling trend beyond this date. Rather, there is evidence that minor warming occurred in the 1980s and 1990s. Evidence of this warming is not restricted to this area, as temperature data from Fairbanks, Bettles, and Gulkana, in Alaska, suggest at least a 1°C step increase in mean annual air temperature after about 1975 (Osterkamp and Romanovsky 1999). Data from Shingle Point and Tuktoyaktuk indicate that this warming has been seen mostly in warmer winter temperatures.

Evidence that warm air temperatures in 1998 resulted in increased thaw penetration in the Richards Island area comes from thaw-depth monitoring sites. Thaw depths were typically over 10 cm greater than any recorded since 1991 and over 20 cm greater at a number of locations. In addition, thawing has been accompanied by ground settlement of between 1 and 7 cm, relative to previous maximums.

Ice-wedge observations also indicate deeper thaw penetration. It is not certain however, whether all of this thawing is attributable to 1998 alone, or is the result of the cumulative effect of increased thaw penetration over several years. On Richards Island, the tops of ice wedges were truncated to a depth of 30 cm. On Richards Island and the Yukon coast, the proportion of secondary and tertiary ice wedges was less than previously observed. Since modern growing roots were seen along the tops of ice wedges in Yukon, thaw may have reached the tops of these ice wedges in years preceding 1998.

Increased thaw penetration may have been accompanied by as much as 20 cm of ground settlement, since depths to tops of primary ice wedges were on average 10 to 20 cm less in 1999 than in 1984 on the Yukon coast (Fig. 5c, d). Since observations in 1984 were taken at the beginning of June and those in 1999 one month later, it is possible that active-layer thickness in 1984 may have been comparatively greater since less thaw had occurred because of the earlier time in the season. However, since 20 cm represents about half of the total depth to the top of ice wedges, and one month represents far less than 50 per cent of the thaw season in that area, the difference in thicknesses cannot be fully accounted for in this way. Rather, it may be attributed, at least in part, to progressive settlement due to increased thaw during these years.

Perhaps the most conclusive evidence of active-layer changes comes from the response of ice wedges (summarized in Fig. 7). An initial active layer with a modern ice wedge (A) is subsequently attenuated (in this case, incrementally), forming a multistage ice wedge (B). A warming event causes partial truncation of this multistage wedge (C). Complete thaw of secondary and partial thaw of primary ice wedges, accompanied by ground settlement, results from increased thaw penetration over multiple years (D). In western Arctic Canada, active-layer attenuation resulting from climatic cooling from the late 1940s and early 1950s to the mid-1970s may have been responsible for the growth and preservation of multistage ice wedges such as those depicted in Figure 5b. Following this, conditions in 1974 and 1983 (the years preceding observations by Mackay (1976) and Harry et al. (1985), respectively) must have been sufficiently cool to preserve secondary and tertiary ice wedges across the region. Certainly, temperature records show that at Tuktoyaktuk and Shingle Point, 1974 was the coldest year on record overall and that 1983 was below the annual average temperature at Tuktoyaktuk (Fig. 2). In addition, both years were typically at or below the long-term 40-year average in most months (Fig. 3a, b).

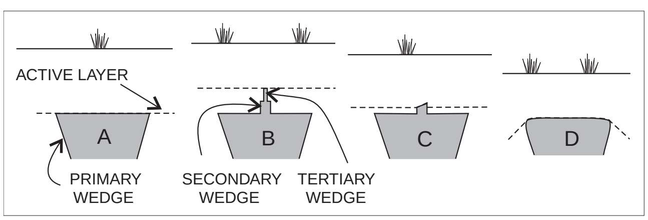

Figure 7. *Schematic diagram illustrating the response of ice wedges to active-layer attenuation and subsequent thickening:* ***A)*** *modern, singlestage ice wedge with initial active layer;* ***B)*** *subsequent active-layer attenuation resulting in multistage ice-wedge growth;* ***C)*** *partial thaw truncation of multi-stage ice wedge as a result of warming and active-layer thickening in a single year;* ***D)*** *complete thaw of secondary and tertiary wedges, partial thaw truncation of primary ice wedge, and accompanying ground settlement resulting from active-layer thickening over multiple years.*

Warm temperatures and increased thaw penetration in 1998 may have resulted in partial thaw truncation of multistage ice wedges across much of this region (as illustrated in Fig. 5c). Indeed, temperatures in 1998 greatly exceed those of 1974 and 1983 in all months (Fig. 3a, b). As previously discussed, it is unlikely that warm temperatures in 1998 could be solely responsible for the complete thawing of secondary and tertiary wedges as well as the partial thaw truncation of primary ice wedges and ground settlement along the Yukon coast; rather, the cumulative effect of warm years following 1983 is likely responsible for ice-wedge truncation. The numerous warm years that occurred prior to 1983, particularly between 1976 and 1981, could have resulted in partial thaw truncation of secondary and tertiary ice wedges. Although temperatures recorded at Tuktoyaktuk after 1983 typically exceed those recorded at Shingle Point in 1983, they do not exceed the maximums recorded between 1976 and 1981. If increased thaw penetration occurred in any of these years and was accompanied by ground settlement from thawing of the tops of the ice wedges and overlying ice-rich organic sediments, then, in succeeding years such as 1998, further thaw penetration could have been facilitated, as overlying material would not have been as thick. This further suggests that if warm years similar to 1998 occur in the future, the impact on ice wedges and thawing of the active layer may be more significant as a result of the decreased thickness of overlying material.

In conclusion, evidence from air temperatures, thaw-depth monitoring and ice-wedge observations indicate that increasing thaw depth and ice-wedge thawing is ongoing, and that 1998 was an extremely warm year in the western Arctic coast that resulted in substantial increases in thaw depths and ice-wedge melting. Although this paper reports on 1999 field evidence based primarily on ice wedges, numerous active-layer detachments seen along the Yukon coast suggest that increased thaw penetration may have had a regional impact in this area. In this context, work is underway to catalogue and catagorize retrogressive thaw flowslides and active-layer detachments along the Yukon coast, to identify the recent changes that have occurred, and to create a baseline record for future observations.

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