Permafrost conditions near shorelines of oriented lakes in Old Crow Flats, Yukon Territory

P. Roy-Léveillée & C. R. Burn
Department of Geography and Environmental Studies, Carleton University, Ottawa, Ontario, Canada.

ABSTRACT
Old Crow Flats is a 4300 km^2 plain in the continuous permafrost of Northern Yukon. It contains over 2500 thermokarst lakes, many of which have rectilinear shorelines and tend to be oriented either NE-SW or NW-SE. Previous explanations of the shape and orientation of the lakes focussed on the underlying geological structure and the propagation of faults through the sediments to cause the alignment of the lakeshores. Permafrost conditions and shore erosion mechanisms observed at forested and tundra sites suggest that wind and patterns of ice-wedge development may be contributing to the occurrence of rectilinear shorelines in the open tundra of Old Crow Flats.

RÉSUMÉ
La plaine de Old Crow est située dans la zone de pergélisol continu, au nord du Yukon. Le nombre de lacs thermokarstiques situés sur cette plaine excède 2500, et plusieurs de ceux-ci ont des berges rectilignes et ont tendance à être orientés soit nord-est-sud-ouest ou nord-ouest-sud-est. Jusqu'à maitenant, les explications avancées pour les lacs d'Old Crow misent sur la structure geologique sous-jacente et la propagation de failles à travers les sédiments forcant l'alignment des berges des lacs. Les conditions thermiques du pergélisol et les mecanismes d'érosion des berges observés dans la tundra et la forêt de la plaine de Old Crow suggèrent qu'en fait le vent et la distribution des coins de glace jouent un rôle important pour le dévelopment de berges rectilignes dans la tundra sur la plaine d'Old Crow.

1 INTRODUCTION

Oriented lakes are groups of lakes possessing a common, preferred, long-axis orientation (van Everdingen 1998). They are common in arctic and subarctic lowlands and have been described from the lowlands of the Alaska coastal plain (Livingstone 1954; Carson and Hussey 1962; Hinkel *et al*. 2005), from the Canadian Beaufort Sea coastal lowlands (Mackay 1963; Harry and French 1983; Côté and Burn 2002), from the coastal lowlands of northern Siberia (Tomirdiaro and Ryabchun 1978; Morgernstern *et al.* 2008), and from other arctic regions including Old Crow Flats in the northern Yukon (Price 1968; Allenby 1989). French (2007) describes several distinct forms of oriented lakes including D-shaped lakes, oval, elliptical, triangular, and rectangular lakes. He divides lake profiles in two broad categories: lakes with littoral shelves surrounding a central deeper part, and shallow saucer-shaped lakes. In most cases, the long axes of the lakes are perpendicular to the prevailing wind direction (Seppälä 2004). The hypothesis that wind-induced currents result in preferential erosion of the ends of the lake and redistribution of sediments along the long-axis shorelines has been proposed to explain lake orientation (Black and Barksdale 1949; Rex 1961; Carson and Hussey 1962; Mackay 1963; Côté and Burn 2002). However, according to French (2007), this hypothesis fails to explain the elongation of small lakes where such currents cannot develop.

In Old Crow Flats, Y.T. (Fig.1), many of the 2500 lakes have rectilinear shorelines and tend to be oriented either NE-SW or NW-SE (Fig 2). The morphology and orientation of the lakes has been attributed to the underlying geological structure (Price 1968; Allenby 1989; Morrell and Dietrich 1993). Allenby (1989) suggested that the rectangular shapes reflect faults in the underlying crystalline basement which have propagated up through the overlying sediment. The hypothesis of geological control on lake shapes is difficult to test in Old Crow Flats, as the Quaternary sediments deposited over the bedrock are over 40 m thick and very little evidence of fault line propagation through the sediments can be found (Morrell and Dietrich 1993). The area is difficult to access, and as a result very little field-based information is available regarding the lakes of Old Crow Flats.

In this paper we contribute to the discussion by investigating permafrost conditions near rectilinear and irregular shorelines in Old Crow Flats. We examine possible relations between mechanisms of shore erosion and lake morphology and orientation.

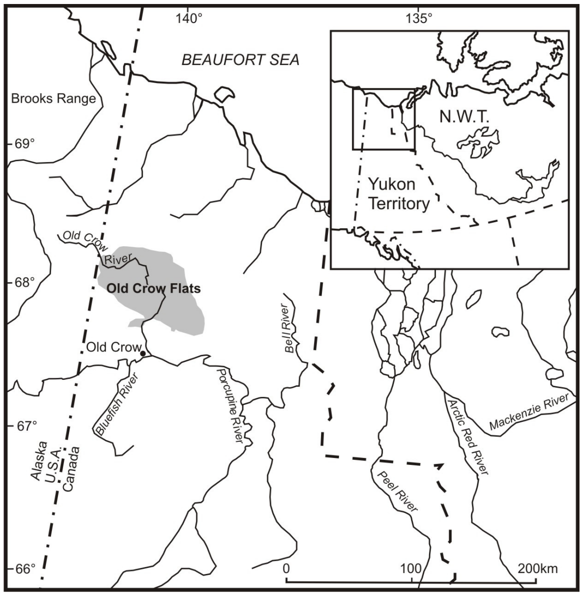

Figure 1. Location of Old Crow Flats, northern YT (modified from Lauriol *et al.* 2009, Fig.1, p. 213).

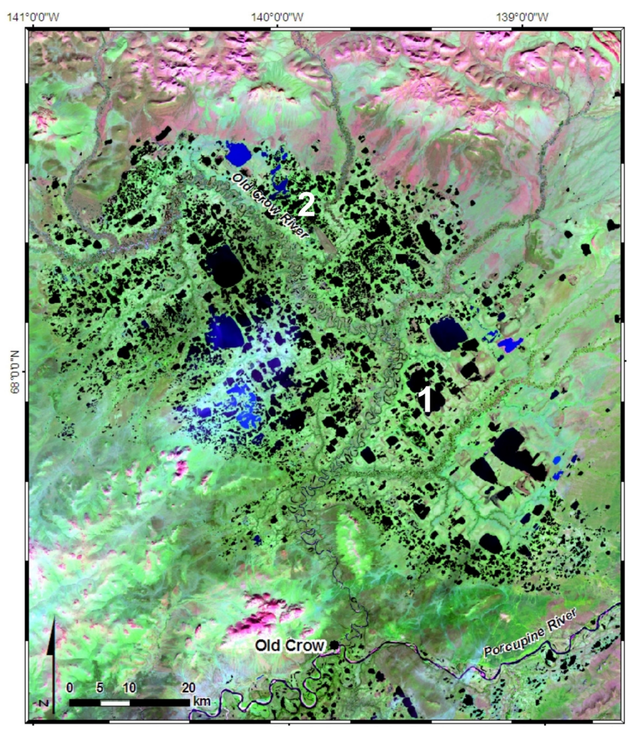

Figure 2. Landsat 7 orthoimage of Old Crow Flats and surrounding areas acquired on August 30th 2001 (reproduced with permission of Natural Resources Canada. All rights reserved). Number 1 and 2 indicate the primary and secondary study areas, respectively.

2 OLD CROW FLATS

Old Crow Flats is surrounded by mountains, with British and Barn Mountains to the north, the Old Crow Range to the west, Richardson Mountains to the east, and the Keele Range to the south. The Flats have a mean elevation of 327 m, with remarkably little elevation change except for the Holocene incision by the Porcupine and Old Crow rivers which are 20 to 50 m below the plain today (Lauriol *et al.* 2002).

Old Crow Flats was not glaciated during the Wisconsinian period, but advances of the Laurentide Ice Sheet about 30 and 17 ka BP blocked eastward drainage and resulted in the flooding of the Bell-Old Crow-Bluefish basins. These flooded basins formed glacial lake Old Crow which deposited up to 10 m of unfossiliferous glaciolacustrine sediment over the thick (near 40 m) layered sands and silts which accumulated in the basin during the Pleistocene (Lichti-Federovich 1973; Hughes *et al.* 1981; Matthews *et al.* 1987; Duk-Rodkin *et al.* 2004; Zazula *et al.* 2004).

Permafrost developed in the freshly exposed glaciolacustrine sediments following the drainage of Glacial Lake Old Crow (Lauriol *et al.* 2009). Measurements of permafrost thickness have not yet been made in the peatlands of Old Crow Flats, nor has ground-ice content been assessed. However, surface features indicative of ice-rich permafrost can be observed in the area, such as high and low centre ice-wedge polygons and retrogressive thaw slumps along river bluffs.

3 STUDY SITES

A number of sites were selected to examine shore erosion and permafrost conditions near rectilinear and irregular lake shorelines. These sites were grouped in 2 study areas (Fig. 2). The first study area (Fig. 3a) is located east of Old Crow River. It includes several small and large lakes with rectilinear shorelines oriented both NE-SW and NW-SE. It also includes several old shorelines and drained lake basins of various ages most of which also have rectilinear shorelines. It is located in a portion of Old Crow Flats characterised by open tundra with patches of shrubs up to 2 m high. The second study area (Fig. 3b) is located in an open spruce shrubland north of Old Crow River, and includes numerous small and irregularly shaped lakes.

4 METHODS.

4.1 Shoreline surveys

Relations between shoreline morphology, local conditions, and erosion mechanisms were observed on all accessible shorelines during two open water seasons (June to September). Randomly located benchmarks were used to assess short-term erosion rates along shorelines.

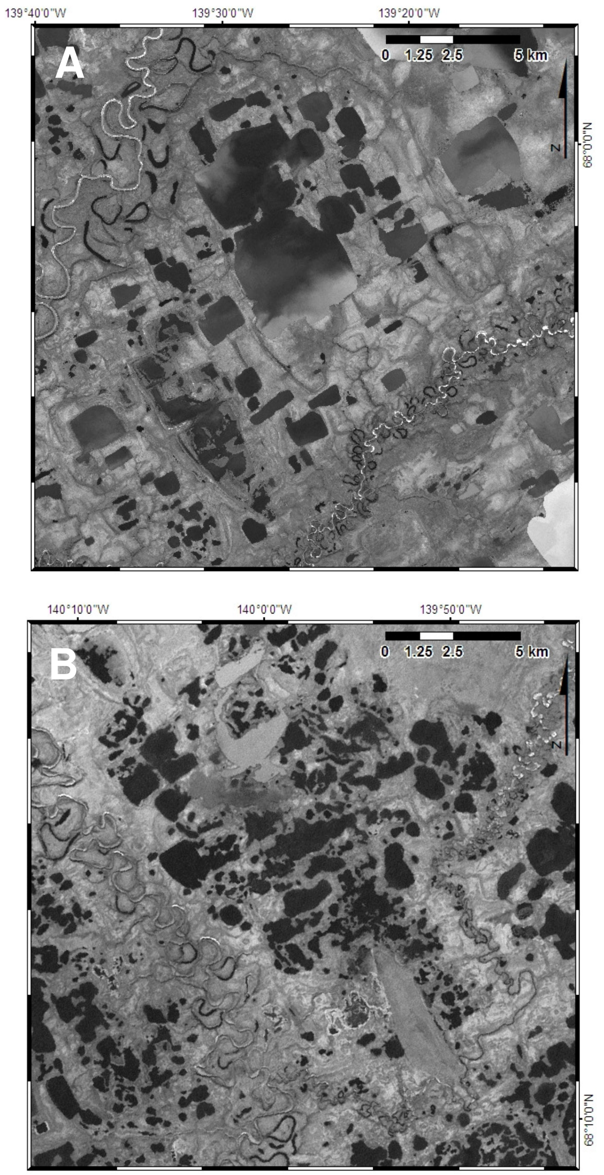

Fig. 3 SPOT satellite imagery (summer 2007) of a) the primary study area and b) Landsat 7 orthoimage of the second study area, located approximately 35 km to the northwest.

4.2 Measurement of permafrost temperatures and snow depth

In both study areas, representative shorelines of different orientation, height, slope, and vegetation cover were equipped with temperatures sensors (Onset Computing, TMC6-HD) installed in the top of permafrost at a depth of 1.25 m below the ground surface. Temperature was recorded at 2-hour intervals with HOBO^{TM} two-channel data loggers (Onset Computing). The thermistors used had a range of -40ºC to 100ºC, an accuracy of ±0.5ºC, and a resolution of ±0.41ºC at 20ºC.

Snow-depth measurements were collected along transects perpendicular to the shoreline, and snow-stratigraphy was described at each instrumented site.

5 SHORELINE EROSION

5.1 Shoreline erosion mechanisms and shore morphology

Three processes of permafrost degradation, as defined in the Russian literature (Aré 1973, 1988), were observed along the lake shorelines: 1) thermal abrasion, which is erosion caused by the thermal and mechanical energy of moving water in contact with permafrost; 2) thermal erosion, which is ground subsidence due to conduction of the thermal energy of water through the ground to the thawing front; and 3) thermodenudation, which is the destruction of shore cliffs under the effect of air thermal energy, solar energy, and gravity.

High banks (> 2 m) are more susceptible to thermal abrasion and thermodenudation due to the exposure of mineral soil in the bank face. As a result, the morphology of high banks can change rapidly in response to varying conditions. Thawed soil slumps to the bottom of the bank and can accumulate if the conditions are calm. This accumulation reduces the bank gradient and insulates the permafrost from the warm air (Fig.4a). If the lake water level is high and the shoreline is exposed to the wind, wave action removes thawed sediments from the slope bottom and prevents accumulation (Fig. 4b). As a result the bank steepens, permafrost remains exposed to the warm air and shoreline recession occurs more rapidly. Under windy conditions, wave action removes material from the bottom of the bank faster than thawed material slumps to the bottom, resulting in the development of niches in the bank (Fig. 4c).

Thermal abrasion seems to play an important role on many shorelines in the open tundra of the first study area, and thermal erosion of permafrost seems to dominate in the second study area (Fig. 4d). However, both processes were observed in both study areas.

5.2 Effects of ice wedges on patterns of shore recession

The erosion of shorelines tends to follow ice wedges. In the case of low shorelines, peat sediments are resilient to wave action and ice wedges are eroded first, resulting in the formation of polygon-shaped peat islands near

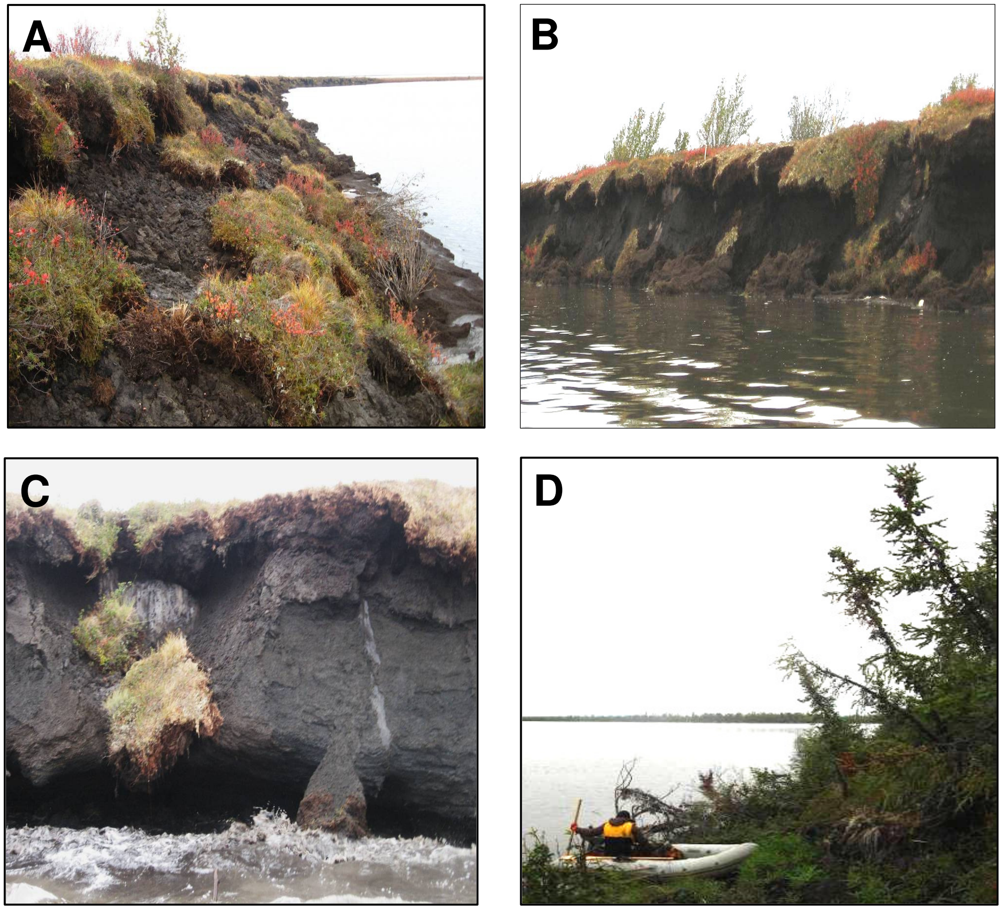

Fig. 4 a) Thaw slumping under calm or low water conditions leads to the accumulation of sediments; b) wave action can prevent the accumulation of sediment and cause a steepening of the bank; c) niches develop when wave action removes material from the bottom of the bank faster than thawed material slumps to the bottom; d) the slow subsidence of lake shores due to thermal erosion is most visible in areas sheltered from wave action and causes trees to lean towards the lake in forested areas, as they respond to mass movement of the bank.

eroding shores. In the case of high shorelines, ice wedges erode more slowly than the largely unconsolidated sediments due to their higher latent heat content, and form a lubricated surface against which thawed sediments can slide.

5.3 Ice push

Shorelines exposed to strong winds in late spring are periodically subject to ice push, which can contribute to accelerating erosion by detaching and removing the vegetation cover (Fig. 5a). Peninsulas and protruding features of the shoreline are particularly vulnerable to the erosive effects of floating ice pushed along or against shorelines by wind action (Fig. 5b). Ice push may contribute to the development of rectilinear shorelines by accelerating the erosion of irregularities in the shoreline.

Observed rates of erosion varied between 0 and 3.5 m/yr. Shorelines receding most rapidly were located where fetch and orientation result in exposure to more aggressive wave action.

5.4 Discussion and implications

The lakes of Old Crow Flats are expanding by thermokarst processes, in some cases rather rapidly. High water levels, wave action, ice push, and the presence of ice wedges accelerate erosion. It is difficult to conceive how the shape of a lake could be determined by underlying geological features and yet be maintained despite permafrost degradation and movement of the shorelines. For example, the 400 m shoreline which is eroding at an average rate of 3.5 m per year is maintaining its rectilinear shape despite its rapid recession. This implies that the rectilinear shape of the shorelines is controlled by something other than underlying fault lines propagating through sediments.

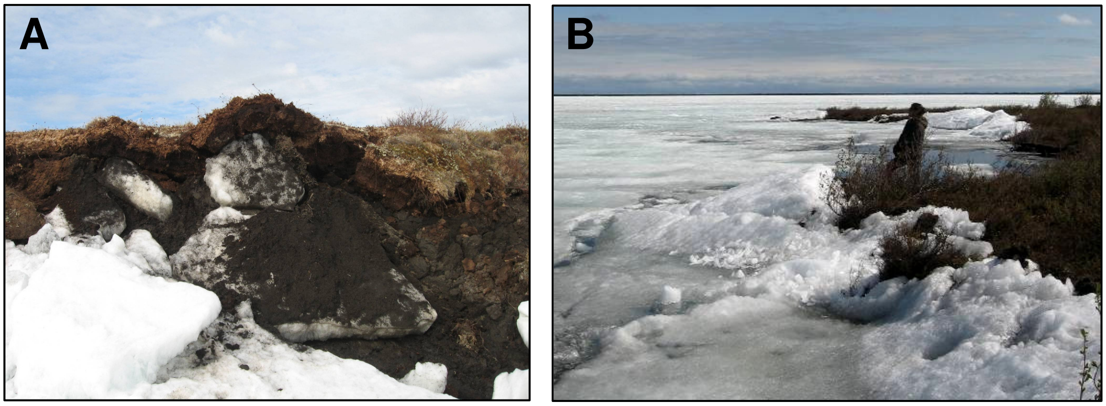

Fig. 5. Ice-push a) accelerates shoreline erosion by damaging or removing the protective vegetation cover and b) protruding features of the shoreline are most easily overridden by the moving ice.

6 PERMAFROST CONDITIONS NEAR SHORELINES

6.1 Permafrost temperatures and snow conditions

Tundra sites were characterised by a vegetation cover of tussocks and ericaceous shrubs over sphagnum peat. Their mean top of permafrost temperature ranged between -5.1ºC and -5.8ºC. In the open spruce shrubland of the second study area, the mean annual temperature at the top of permafrost was between -3.4ºC and -3.7ºC (Table 1). These differences in mean temperature are likely associated with differences in snow conditions observed at each location. The snow cover is generally thicker and has a lower density at the second study area, providing better ground insulation than the thinner and denser snow cover found at the tundra sites in the first study area (Table 1).

6.2 Ice wedge abundance

Ice-wedge polygons are well developed and omnipresent in the tundra of the first study area. They are clearly visible from the air (Fig. 6), and along the shorelines where they are either exposed in rapidly eroding banks, or form depressions in the bank on slowly eroding shorelines. In the second study area, ice wedges are rare, and have been observed only in patches of tundra with a low vegetation cover. No ice wedges were found in forest in Old Crow Flats during two summers of fieldwork. No ice wedges were visible along forested shorelines and in patches of forest we found no troughs and no trees tilting towards each other (Kokelj and Burn 2005). The difference in ice-wedge abundance between the two study areas may be related to the difference in snow cover and ground temperature.

The ice-wedge networks surrounding the lakes are strikingly orthogonal over extensive areas in Old Crow Flats (Fig. 6). Orthogonal ice-wedge networks develop where sediments undergo their initial freezing under conditions of anisotropic thermal contraction stress where a source of heat reduces the thermal stress in one direction and cause ground cracking to occur at 90^{o} to the edge of the heat source (Lachenbruch 1962). Extensive orthogonal networks such as seen in Old Crow Flats (Fig. 6) may have developed where lakes slowly regressed or drained in stages.

Table 1. Annual mean ground temperature (2008-09) and snow conditions (April 2010) in the two study areas, for different vegetation covers.

Study area	Vegetation	# of sites	TTOP (ºC)	Median Snow depth (cm)	**Snow density (g/cm^3)**
1	Dwarf shrubs	5	-5.1 to -5.8 (n=5)	26 (4 transects)	**0.29 (n=8)**
2	Open spruce shrubland	4	-3.4 to -3.7 (n=4)	52 (4 transects)	**0.19 (n=4)**

Figure 6. Ice-wedge networks are orthogonal over extensive areas in Old Crow Flats.

6.3 Discussion and implications

The lakes of Old Crow Flats that are square and oriented tend to be concentrated in areas characterised by open tundra, where extensive orthogonal ice-wedge polygons have been observed. The effects of ice wedges on shoreline erosion described above and the association of rectangular ice wedge networks and rapidly expanding rectangular lakes suggests that patterns of ground-ice development may contribute to the evolution of rectilinear shorelines in the open tundra of Old Crow Flats.

It is important to note that rapidly eroding rectilinear shorelines have also been observed in areas where the ice wedges are not orthogonal, highlighting the probable importance of other factors in shaping straight lake edges.

7 WIND REGIME AND SHORE EROSION

7.1 Wind direction and lake orientation

The dominant wind directions during the open water season (June to September) at the first study area are NE and ENE, while at the Old Crow Airport dominant wind directions are NE and NNE (Fig. 7). The small difference in orientation may be due to effect of local topography between Old Crow and Old Crow Flats.

The lakes of Old Crow Flats are oriented both perpendicular and parallel to this direction. The consistency between the long-axis orientation of many elongated lakes and wind direction in Old Crow Flats indicates that lake orientation is not due to the wind-driven processes associated with orientation of lakes on Tuktoyaktuk Peninsula and the North Slope of Alaska. However, observation of shore erosion mechanisms clearly indicates that wind is an important factor in the development of the lakes of Old Crow Flats.

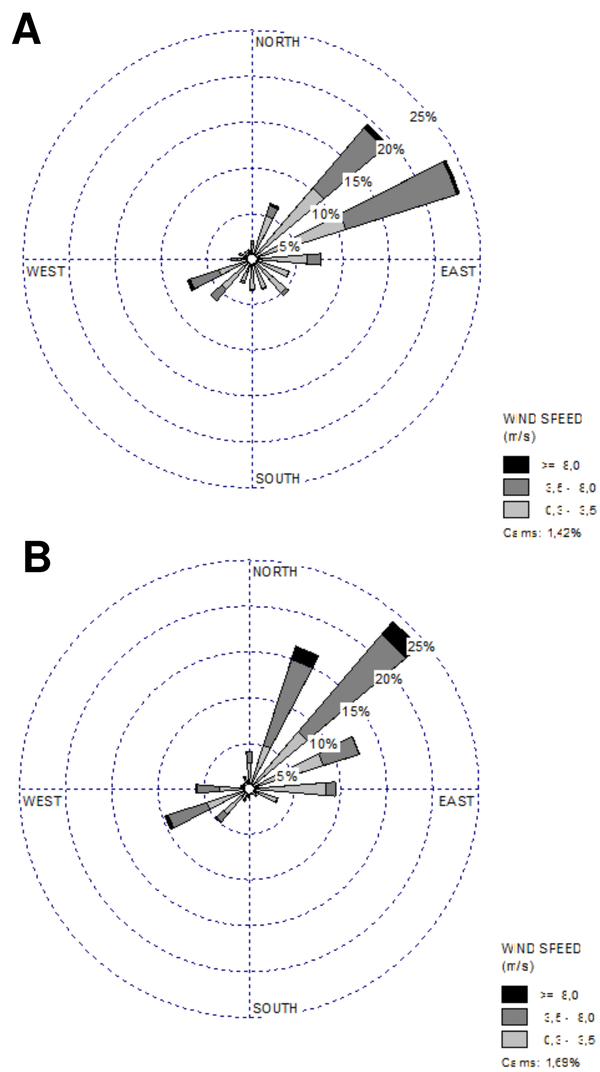

Figure 7. Wind speed and direction distribution for the open water season (June to September) 2008 and 2009 a) in the first study area, and b) at the Old Crow airport.

8 CONCLUSIONS

Field observations confirm that the lakes of Old Crow Flats expand by thermokarst processes and the rapid recession rates of some rectilinear shorelines indicate that their morphology is not controlled by the structural geology of the area. The form of the rectilinear lakes may be associated with the orthogonal networks of ice wedges in the study area. While lakes with irregular shorelines tend to be clustered in open spruce forest, oriented lakes with rectilinear shorelines are clustered in the open tundra, where the snow is thinner, the ground colder, and orthogonal ice-wedge polygons are abundant. Ice-wedges clearly affect shore erosion patterns, but the occurrence of rectilinear shorelines in areas where ice-wedge polygons are not orthogonal indicates that other factors also contribute to lake shape.

The relation between the local wind regime and the bi-modal orientation of the lakes indicates that the relation between lake orientation and wind regime described at other arctic locations does not apply here. The effect of the wind is likely still crucial to lake development considering the importance of ice push and wave action to shore erosion.

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