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Icebergs as windvanes: Late Pleistocene iceberg scours in the eastern Great Lakes record the glacial anticyclone

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ABSTRACT

Ice sheets and atmospheric circulation are tightly coupled, yet gaps remain in defining glacial anticyclonic wind patterns in both models and proxy data. Using high-resolution digital elevation models, we discovered >3000 relict iceberg scour marks on Late Pleistocene proglacial lake beds spanning >1000 km in the eastern Great Lakes, USA. We propose that iceberg scour marks spanning the last deglaciation (ca. 17–12 calibrated k.y. B.P.) act as paleowind proxies that record the anticyclonic wind system fronting the Laurentide Ice Sheet. Easterly winds steered iceberg drift, producing scour marks oriented WSW (258° ± 19°), the same general orientation as regional dune fields and longshore drift. Relict thermokarst lakes discovered in our study area are found to be impacted by the same wind system. Our discoveries provide the most extensive record of relict iceberg scour marks in the Great Lakes and offer evidence for sustained easterly winds driven by the Laurentide Ice Sheet glacial anticyclone fronting ~5000 years of ice sheet recession.

INTRODUCTION

Near-surface atmospheric circulation patterns change on glacial-interglacial and millennial time scales as a function of shifting ice sheet configurations (Löfverström et al., 2014). During the Late Pleistocene and into the early Holocene (ca. 20–8 calibrated k.y. B.P.), paleowind proxy data and model simulations reveal the existence of near-surface easterly winds within ~150–200 km of the Laurentide Ice Sheet margin (Arbogast et al., 2015; Conroy et al., 2025; Dalton et al., 2020; Schaetzl et al., 2016). These winds arose from a persistent atmospheric high-pressure system over the Laurentide Ice Sheet that resulted in anticyclonic circulation encircling the ice sheet and katabatic winds descending its surface (Conroy et al., 2025). Although broad agreement exists, the width and timing of the easterly wind belt remain uncertain (Conroy et al., 2025). Anticyclonic circulation in the northern United States had a significant impact on regional climate (e.g., Griggs et al., 2022), eolian processes (e.g., Carl et al., 2023), and longshore drift (e.g., Schaetzl et al., 2016). Paleowind trends have been gathered from various proxies, such as dunes (David and Gadd, 1988), spits (e.g., Schaetzl et al., 2016), drainages (e.g., Hallberg, 1979), loess deposits (e.g., Sweeney et al., 2004), tree rings, and tamarack (*Larix laricina*) prevalence (Griggs et al., 2022). These paleowind proxies are signs of paleowind direction throughout deglaciation and during the Last Glacial Maximum (ca. 17–12.9 ka). Only 10 out of 81 published records show easterly trending winds, with the rest recording westerly winds (Conroy et al., 2025). So, there are few published proxy data characterizing easterly trending winds throughout this time.

Iceberg scour marks (or plough marks) form as drifting icebergs become grounded and carve their bed. Once produced at calving fronts along water-terminating ice margins, icebergs drift with influences by wind, currents, bathymetry, and the concentration of sea ice (Collares et al., 2018; Schodlok et al., 2006). As icebergs drift into shallows, they carve a trench in the bed, which records iceberg movements (Fig. 1C). Schodlok et al. (2006) and Lichey and Hellmer (2001) observed that wind acting on the exposed part (above the water) of isolated icebergs dominates iceberg drift direction. This principle motivates us to investigate the use of iceberg drift direction as a paleo-windvane. During the last deglaciation, southern Laurentide Ice Sheet calving fronts delivered icebergs into proglacial lakes and marine estuaries (ca. 17–12 ka) (Dalton et al., 2020; Franzi et al., 2025). These proglacial water bodies existed within the easterly wind belt, with drifting icebergs leaving their marks on former lake and estuary beds (Figs. 1B and 1C). This allows us to explore iceberg scour marks across >1000 km of former ice margin as an ~5-k.y.-long record of paleowind direction (Fig. 1A).

Through the use of iceberg scour marks, we present evidence for an anticyclonic easterly wind system spanning ~5 k.y. through the last deglaciation. Our iceberg-based paleowind record aligns with the orientations recorded in regional dunes, spits, and thermokarst lakes, capturing the longest record of easterly winds in eastern North America (Fig. 1A). Unlike other paleowind proxies, iceberg scour marks form near and move with the Laurentide Ice Sheet margin, allowing for a continuous record of anticyclonic winds.

ICEBERG SCOURS

We digitized iceberg scour marks using shaded relief (azimuth and altitude of 315° and 45°, respectively) derived from publicly available 0.5–2-m-resolution bare-Earth digital terrain models in ArcGIS Pro 3.5.2 (Figs. 1–3; Figs. S1–S11 in the Supplemental Material[1]). Scour marks were identified as curvilinear trenches, 0.5–5 m deep, sided by berms. We traced polylines along each trench and extracted orientations via the "calculate geometry" tool in their attribute table (Fig. S12) (vertical datum, North American Datum of 1983; horizontal datum, Universal Transverse Mercator zones 18N, 17N, and 16N). The "calculate geometry" tool for line bearings takes the start and end node of each

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[1]Supplemental Material. Thirty supplemental figures display further examples of scour marks and their characteristics, while the rest showcase more rose diagrams of the scour marks, dunes, and relict permafrost. Included are details on their characteristics, locations, and visual details showing how they were mapped. Please visit https://doi.org/10.1130/GEOL.S.32048346 to access the supplemental material; contact editing@geosociety.org with any questions.

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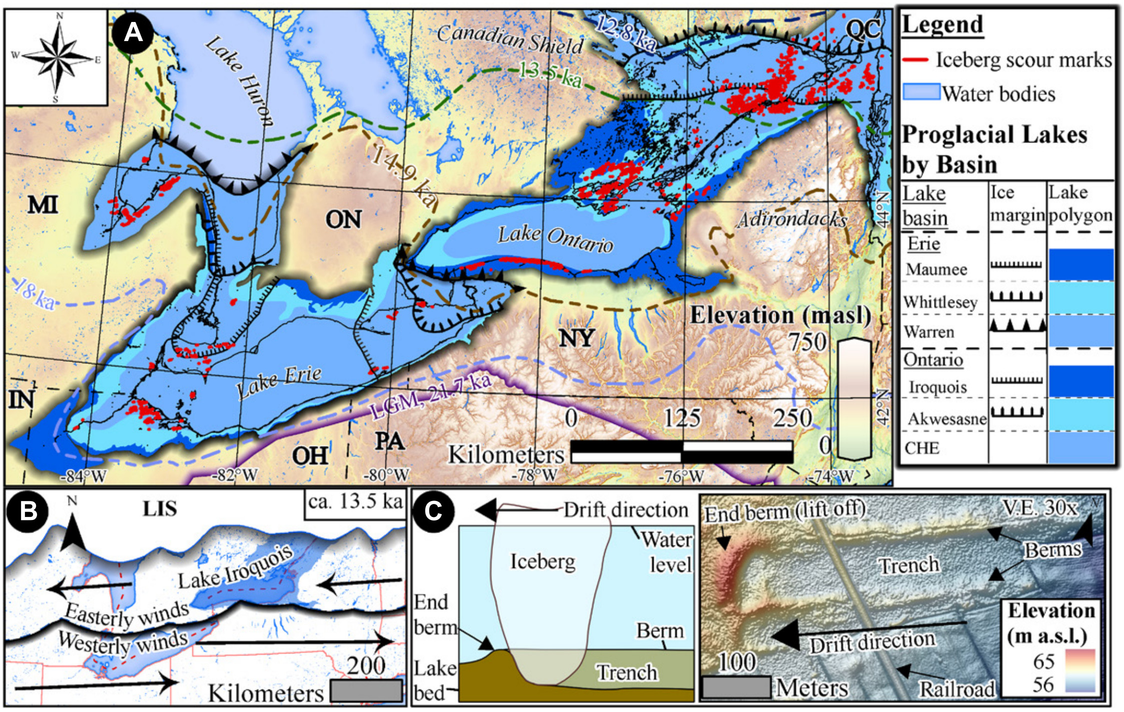

Figure 1. (A) Distribution of scour marks (red) in eastern Great Lakes showing glacial lakes and their ice limits. Dashed colored lines mark the extent of former ice margins (from Dalton et al., 2020). The lake phases are from Calkin and Feenstra (1985) and Franzi et al. (2025). (B) Depiction of easterly-westerly wind belt at 13.5 ka. LIS is Laurentide Ice Sheet. Wind belt is at most 200 km from ice margin (Schaetzl et al., 2016). Ice limits and lake phases are from Dalton et al. (2020), Calkin and Feenstra (1985), and Franzi et al. (2025). (C) Left panel shows 2-D side view of iceberg forming scour mark. Right panel is viewing a scour mark, top down, and reviews general morphology shown by a scour mark (location in Fig. 2). MI—Michigan; NY—New York; OH—Ohio; ON—Ontario; PA—Pennsylvania; QC—Quebec; CHE—Champlain-Hochelagan Estuaries; LGM—Last Glacial Maximum; masl—meters above sea level; V.E.—vertical exaggeration.

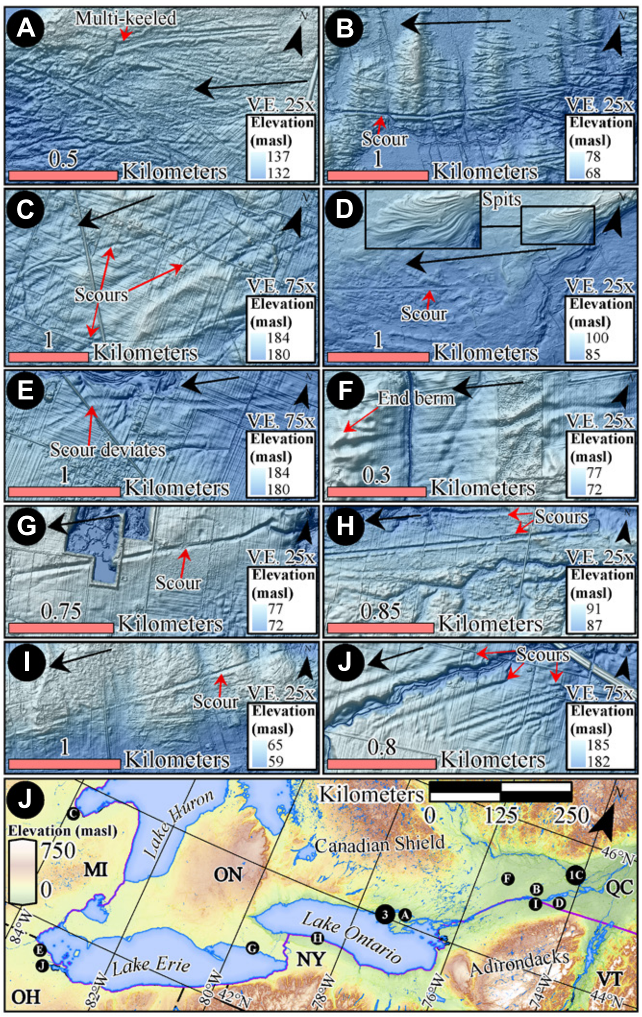

Figure 2. (A–J) Iceberg scour marks in eastern Great Lakes region; locations are shown in panel K. Notice large black arrows showcase general drift direction in each panel, while smaller red arrows are pointing toward scours. (A) Multi-keeled iceberg scour. (B, C) Various scour marks. (D) Scour mark close to developing spits. (E) Scour mark deviating in its drift pathway. (F) Scour mark showing an end berm, an example of iceberg lift-off. (G–I) Scour marks illustrating icebergs colliding into hillsides. (J) Multiple scours. (K) Map of locations for panels A–J and for Figures 1C and 3. MI—Michigan; NY—New York; OH—Ohio; ON—Ontario; QC—Quebec; VT—Vermont; V.E.—vertical exaggeration; masl—meters above sea level.

polyline and measures the horizontal distance between these two nodes. Because most of the scour marks are linear, this tool can measure their orientations with accuracy. Prior studies noted some scour marks near Toronto, Canada (Eden and Eyles, 2002), and along the U.S.-Canadian border (Delage and Gangloff, 1993), regions where we reveal many more scour marks. We reinterpreted as relict iceberg scour marks features in the Lake Erie basin mapped by Grass and Pilkington (1985) as modern-day scouring.

The mean length of the 3377 iceberg scours is 533 ± 640 m; many extend several kilometers (Fig. S13). Iceberg scour widths vary between <10 and 60 m, and their relief is <5 m (Figs. 2 and 3). The scours are mostly linear with some curvilinear trenches sided by 0.5- to 5-m-tall berms; a few deviated from their linear paths (Figs. 2B and 2E–2G; Fig. S13). The tallest icebergs were >100 m thick based on comparisons between scour mark elevation and the elevation of nearby proglacial lake shorelines. The regional mean bidirectional trends are: 250° ± 24° (Lake Erie basin), 260° ± 18° (Lake Ontario basin), and 257° ± 19° (St. Lawrence Lowlands), giving an overall mean trend that is WSW-ENE, 258° ± 19° (Fig. 4).

We subdivided scour marks by the proglacial lake stages in which they formed via their context with nearby paleo-shorelines and ice margins. In instances where it is known what lake a scour mark formed in, it was categorized as belonging to each lake stage it could have been

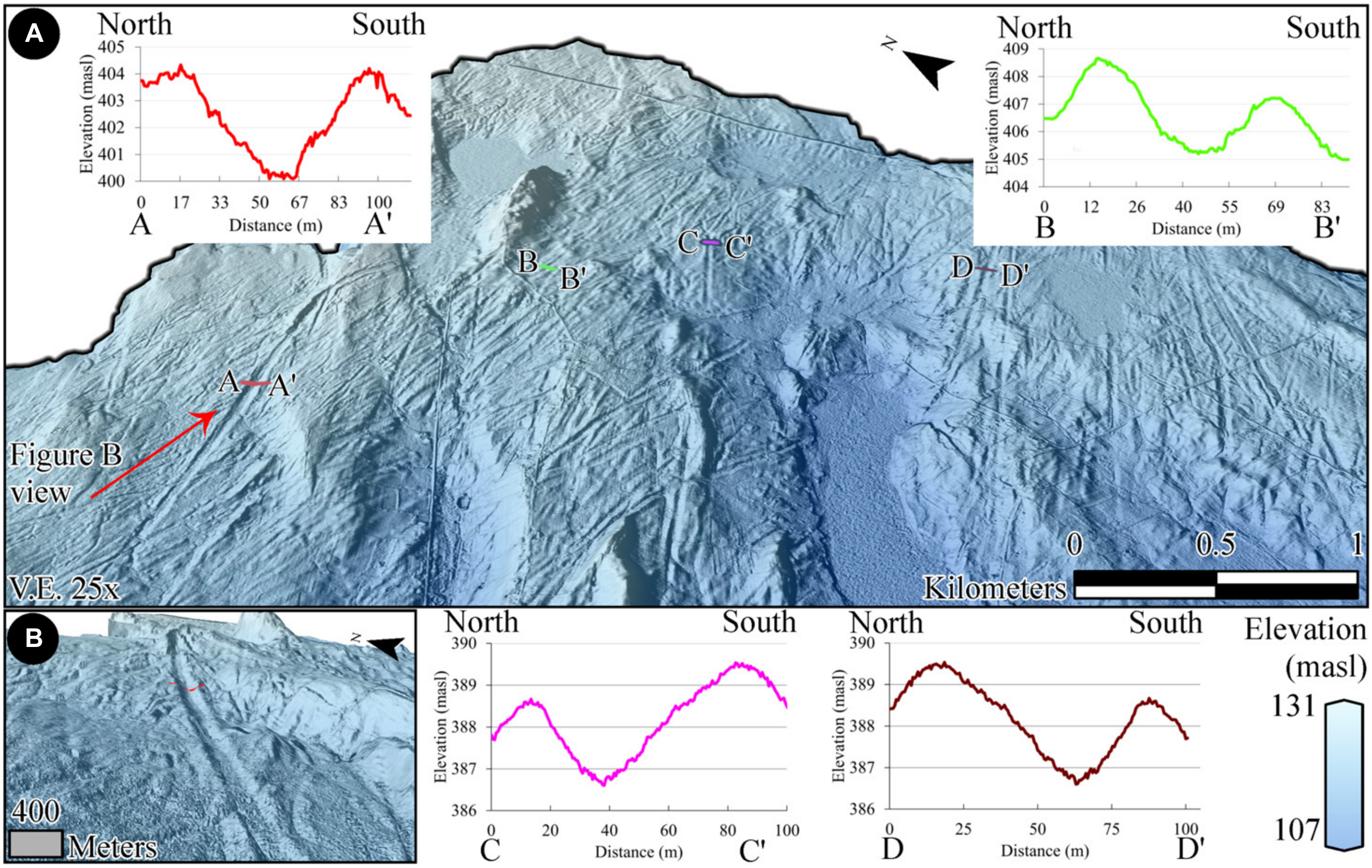

Figure 3. Lake Iroquois iceberg scour marks in Prince Edward County, Ontario, Canada (location shown in Fig. 2). V.E.—vertical exaggeration; masl—meters above sea level.

in. Scour marks in the Lake Erie basin formed between ca. 17.4 and 14.7 ka in proglacial lake stages Maumee, Arkona, Whittlesey, and Warren (e.g., Dalton et al., 2020; Lewis et al., 2022). Scour marks in the Lake Ontario basin and near Quebec formed between ca. 14.5 and 12.5 ka in proglacial lake stages Iroquois, Abenaki, and Akwesasne and the Champlain and Hochelagan Estuaries (Franzi et al., 2025). In dividing the scours marks by lake stages, we found no significant differences in orientations (Figs. S14 and S15).

ICEBERGS AS WINDVANES

We suggest that iceberg scours in proglacial lakes associated with the Laurentide Ice Sheet serve as paleowind proxies. We obtain iceberg drift direction in instances of iceberg shoaling (Figs. 1C, 2A, and 2F); when icebergs drift into shallow water, they form a scour mark ending in a berm (Figs. 1C and 2F). Every example of iceberg shoaling and lift-off (we found 22 well-preserved examples) has a westward drift direction. This is consistent with the easterly winds. We believe currents played a minimal role in steering icebergs. This is because of the high degree of consistency in scour mark orientation, and iceberg scours are not oriented toward paleo–lake outlets (except for eight scour marks in Lake Abenaki; Fig. S15). Furthermore, iceberg scours are oriented to the SW in basin centers and sides in patterns that do not align with modern-day gyre-dominated lake circulation (Beletsky et al., 1999). Given this evidence, we propose that relict iceberg scour marks serve as a reliable paleowind proxy.

We also digitized parabolic dunes, obtaining the wind direction by tracing their long axes. We extracted wind direction from dunes by tracing a line through their fold axes (Fig. S12). The orientation of the dunes was measured and extracted using the "calculate geometry" tool. The paleowind directions of parabolic dunes in the southern portion of the St. Lawrence Lowlands (Potsdam dunes) are 236° ± 5.4°, whereas those in the north are oriented 249° ± 9° (Quebec dunes) (Fig. 4).

We reveal new evidence for relict thermokarst lakes in the eastern Great Lakes (Fig. 4; Fig. S16). We interpret ellipse-shaped depressions in the St. Lawrence Lowlands as relict thermokarst lakes because their geometry is similar to that of modern thermokarst lakes in the Arctic (Figs. S18–S20). Sly and Prior (1984) reported relict thermokarst lakes within the subsurface of the modern Lake Ontario basin, near these same features. It has been recognized that ellipse-shaped thermokarst lakes form perpendicular to the prevailing wind direction (French, 2018; Grosse et al., 2013). Thus, we extracted the basin orientations by tracing the long axes and then following methods mentioned before. Only intact thermokarst lakes were mapped (complete ellipses). The paleowind direction of the relict thermokarst lakes in the St. Lawrence Lowlands are oriented 238° ± 10° (Fig. 4), whereas those in southwestern Ontario near Lake Huron are oriented 268° ± 6.3° (Fig. S16).

Iceberg scours, dunes, and thermokarst lakes collectively document consistent easterly winds following deglaciation (Fig. 4). Our measured orientations of iceberg scour marks align with the wind direction of Late Pleistocene dune fields and thermokarst lakes (Carl et al., 2023; David and Gadd, 1988). The relict thermokarst lakes in the St. Lawrence Lowlands were found to be oriented perpendicular to dunes in the same region (Potsdam dunes) (Fig. 4). The dunes have a wind direction of 236° ± 5°, while thermokarst lakes in the St. Lawrence Lowlands are orientated 238° ± 10°. This supports prior findings that thermokarst lakes are oriented with their long axes perpendicular to prevailing wind directions (French, 2018; Grosse et al.,

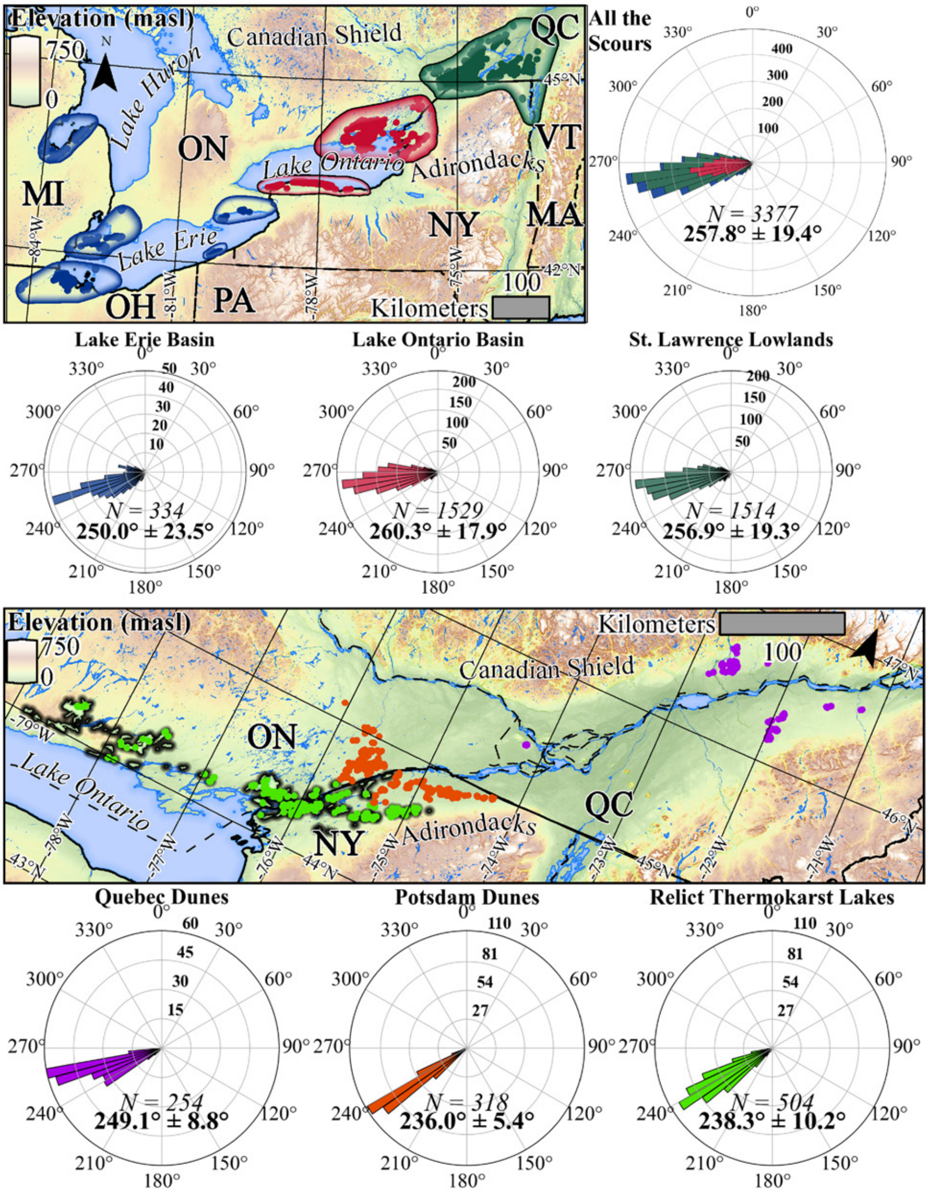

Figure 4. Unidirectional rose diagrams displaying drift direction of scour marks and paleowind direction of regional dunes and relict thermokarst lakes. Rose diagrams of scour marks are divided by region, as shown by map in top left corner. Dunes and thermokarst lakes are shown on map in middle of figure. MA—Massachusetts; MI—Michigan; NY—New York; OH—Ohio; ON—Ontario; PA—Pennsylvania; QC—Quebec; VT—Vermont; masl—meters above sea level.

2013). These thermokarst lakes along with the dunes likely formed after the Champlain Estuary drained, between ca. 12.5 and 12 ka. This was when the ice margin was still 150–200 km away and when the dunes in the southern region of the St. Lawrence Lowlands (Potsdam dunes) could have formed. Finally, longshore drift was observed by Franzi et al. (2025) to support anticyclonic winds as well (Fig. 2D).

The extent of the anticyclonic winds from the Laurentide Ice Sheet margin was observed in northern Michigan; easterly winds extended ~150–200 km from the ice margin, dominating the development of beach spits around glacial Lake Algonquin that were within this zone (Schaetzl et al., 2016). These winds then transitioned to westerly winds beyond this zone, forming dunes in the opposite direction (Arbogast et al., 2015; Schaetzl et al., 2016). This same phenomenon is seen around in the Adirondack Mountains. Dune fields in the St. Lawrence Lowlands dating to ca. 12.5–12.0 ka record easterly winds (e.g., Carl et al., 2023; Filion, 1987), while those farther south in Rome Sand Plains (ca. 13–11 ka), Albany Pine Bush–Saratoga Sand Plains (ca. 12.5–11 ka), and Ohio (ca. 13.1–8.2 ka) show a westerly trend during the same time frame (Campbell et al., 2011; Murari et al., 2016; Wolfe et al., 2025). The dune fields in the southern portion of the St. Lawrence Lowlands formed from easterlies ~150–200 km from the ice front (Carl et al., 2023); they trend in the same direction as nearby iceberg scour marks. Anticyclonic winds in the eastern Great Lakes had a significant impact on the regional climate. Easterly winds would have resulted in lake-effect precipitation on the western shores of the Great Lake basins, the opposite direction from that seen today (Griggs et al., 2022). Variables that contribute to lake-effect precipitation are fetch, wind speed and direction, atmospheric stability, ice cover, topography, and lake-air temperature differences (Holroyd, 1971; Laird et al., 2003; Vavrus et al., 2013). Considering Pleistocene lakes were larger, broader, and deeper than their present-day counterparts during this time period, lake-effect precipitation may have even been amplified (Griggs et al., 2022). Regional lake-effect climate was suggested by Griggs et al. (2022) to have impacted regional climate during the Bølling-Allerød and Younger Dryas climatic events, leading to differences between regional and hemispheric paleoclimate records.

Our discovery of widespread iceberg scour marks throughout the eastern Great Lakes could be built upon to track patterns of atmospheric circulation across North America throughout the last deglaciation. Iceberg scour marks compiled across the continent could record the glacial anticyclone across space and time. This would refine the easterly wind belt's width and offer a continuous record of winds tracking the retreating Laurentide Ice Sheet. In modern-day Lake Superior (Wattrus et al., 2006), in the glacial Lake Agassiz basin (Clayton et al., 1965; Dredge, 1982), and near the Great Slave Lake, Canada (Weber, 1958), relict scour marks have been noted. This sparks the need for high-resolution terrain datasets for these areas to characterize the evolving glacial anticyclone throughout the Late Pleistocene and into the Holocene.

The impact of the anticyclonic wind system in the eastern Great Lakes extends beyond its regional effects on climate. Mapping the belt of anticyclonic winds from proxy data can constrain the proximity of an ice margin. For the eastern Great Lakes region, a westerly trending paleowind proxy would imply the ice margin was >150–200 km away. Easterly trending winds would imply the ice margin was within 150–200 km. Considering that anticyclonic wind belts evolve with the ice margin means that dated paleowind proxies can constrain the Laurentide Ice Sheet configuration. If other ice sheets have anticyclonic wind belts, this approach could be used elsewhere. Pairing landforms as paleowind proxies with radiocarbon and optically stimulated luminescence dating could further improve our understanding of the climate and atmospheric circulation through the last deglaciation.

CONCLUSION

The glacial anticyclone had a continental-scale impact on North America throughout the Late Pleistocene. We find iceberg scour marks can be used as a paleowind proxy and provide a long record of the glacial anticyclone spanning ca. 17–12 ka. These anticyclonic winds had a significant impact on the development of the regional landscape in the form of dunes, longshore drift, thermokarst lakes, and regional climate. Geomorphic evidence for the anticyclonic wind belt could also constrain the proximity of an adjacent ice margin. We show how iceberg scour marks can be used across widespread areas as a paleowind proxy and suggest extending this record throughout North America spanning the entire last deglaciation.

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