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Progressive increase in number and volume of ice-marginal lakes on the western margin of the Greenland Ice Sheet

Jonathan L. Carrivick *, Duncan J. Quincey

School of Geography, University of Leeds, Woodhouse Lane, Leeds, West Yorkshire LS2 9JT, UK

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ABSTRACT

The evolution in number, area and volume of ice-marginal lakes in western Greenland is very poorly documented or understood. It is important to understand ice-marginal lake evolutions because they provide an element of meltwater retention, affect ice-margin character and behaviour, and potentially glacier dynamics. This study uses repeat satellite imagery acquired between 1987 and 2010 to reveal a net 44% (±6.5%) increase in the number of lakes, a net 20% (±6.5%) expansion in total lake surface area and an increase of 12% (±3.3%) in the estimated volume of meltwater retained along a 1300 km length of the ice margin in western Greenland. Whilst ~12% (±1.6%) of the ice margin holds lakes at any one time there is considerable complexity in lake evolution; many lakes have coalesced, drained partially or fully, or become detached from the ice margin. The total lake volume equates to 144% of the annual runoff combined from Gothab and Jakobshavn hydrological catchments. The rate of increase in meltwater retention between 1987 and 2010 was similar to the rate of increase in ice sheet surface runoff over the same time period. If the study region is representative of the whole Greenland Ice Sheet margin then as a first-order estimate ~5% of the increased runoff over the last 25 years has been intercepted en route to the oceans by the increased ice-marginal lake capacity. Interactions between these ice-marginal lakes, the western Greenland Ice Sheet and climate should be determined to provide insight into future land-terminating ice-marginal conditions, runoff retention and meltwater and sediment fluxes to the oceans.

1. Introduction

Approximately 60% of the Greenland Ice Sheet (GrIS) drains meltwater to a terrestrial margin (Lewis and Smith, 2009) and in detail this includes both land-terminating and lacustrine-terminating glaciers. This detail is important because lacustrine-terminating glaciers can have a character and behaviour that are fundamentally different to land-terminating glaciers (Table 1). Lacustrine-terminating glaciers can also exhibit activity that contrasts with tidewater glaciers (e.g. Larsen et al., 2007), possibly due to less submarine melting (Trüssel et al., 2013). Outside of Greenland, some lacustrine-terminating glaciers are regarded as being potentially decoupled from climate (Warren, 1991; Chinn, 1996; Warren and Kirkbride, 2003). Ice-marginal lakes can affect the character and behaviour of glaciers due to promoted thermo-mechanical erosion, buoyancy and subglacial water pressure (Carrivick and Tweed, 2013; Table 1), especially during rapid fluctuations in water level (e.g. Walder et al., 2006; Kingslake and Ng, 2013; Tsutaki et al., 2013). Interactions between ice-marginal lakes can produce glacier outburst floods or 'jökulhlaups', such as those recently examined in western Greenland by Russell et al. (2011), Weidick and Citterio (2011) and Carrivick et al. (2013). Furthermore, ice-marginal lakes are a receptor of ice sheet ablation and the position, character and behaviour of meltwater outlets can give insight to contributing water source dynamics (c.f. Lewis and Smith, 2009), which is of importance to improving understanding of ice-sheet runoff. However, no large-scale analysis of these effects has been made and neither has there been documentation and systematic analysis of changes in the area and volume of ice-marginal lakes at the terrestrial margins of the Greenland Ice Sheet. In this paper we therefore provide the first systematic documentation and analysis of ice-marginal lakes in western Greenland and discuss the implications of this meltwater retention.

2. Data and methods

Landsat MSS (60 m pixel resolution), TM (30 m) and ETM+ (30 m) Level 1T (orthorectified) images were obtained from the USGS archive (Table 2) for a continuous 1300 km length (~25% of the total) of the Greenland ice margin (Fig. 1). We focussed on western Greenland and primarily on five year groups; 1987, 1992, 2000, 2005 and 2010 (Table 3) to provide coverage of the study area at regular temporal intervals. Images were selected to coincide with the peak melt season (July, August) to avoid snow cover or frozen lake surfaces. Images

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* Corresponding author. Tel.: +44 113 343 3324.
E-mail address: j.l.carrivick@leeds.ac.uk (J.L. Carrivick).

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Table 1
Summary of the difference in character and behaviour between land-terminating and lacustrine-terminating glaciers. Note many of these factors are inter-dependent. Example references are those where the differences are explicitly documented, whereas indicative references are those from which the differences can be inferred.

	Land-terminating glacier margin	Lacustrine-terminating glacier margin	Example references	Indicative references
Character				
Ice margin position	More likely slower retreat	More likely faster retreat due to calving and thermo-mechanical erosion	Warren, 1991; Chinn (1999); Larsen et al. (2007); Trüssel et al. (2013)	
Subglacial drainage system	Less likely to be distributed	More likely to be distributed		Kingslake and Ng (2013)
	–	More likely vertical extension into ice		Harper et al. (2010)
Basal water pressure	lower	higher		Tsutaki et al. (2011)
Behaviour				
Ice velocity	lower	Faster due to increased sliding due to higher basal water pressure		Kirkbride and Warren (1999); Naruse and Skvarca (2000); Diolaiuti et al. (2006); Röhl (2006); Boyce et al. (2007)
Calving	Dry calving unlikely	More likely. Rate can approach that of tidewater glaciers. Lake-terminating more likely to have floating tongue than tidewater	Warren (1991); Warren and Aniya (1999); Warren and Kirkbride (2003)	Pelto and Warren (1991); Kirkbride and Warren (1999); Diolaiuti et al. (2006); Röhl (2006); Trüssel et al. (2013)
Flotation, flexure and fracture	Much less likely	More likely		Tsutaki et al. (2013)

Table 2
Attributes of satellite imagery used in this study.

Year group	Sensor	Scene ID	Date of acquisition	Path	Row
2009–2011	ETM+	LE70020172011231EDC00	19/08/2011	002	017
	ETM+	LE70040162009207EDC00	26/07/2009	004	016
	ETM+	LE70040172009207EDC00	26/07/2009	004	017
	ETM+	LE70060152011211ASN00	30/07/2011	006	015
	ETM+	LE70070132010231EDC00	19/08/2010	007	013
	ETM+	LE70070142011234EDC00	22/08/2011	007	014
	ETM+	LE70090112009210EDC00	29/07/2009	009	011
	ETM+	LE70090122010229EDC00	17/08/2010	009	012
	ETM+	LE70100102009217ASN00	05/08/2009	010	010
2004–2007	ETM+	LE70020172004244ASN01	31/08/2004	002	017
	ETM+	LE70040162007202EDC00	21/07/2007	004	016
	ETM+	LE70040172007202EDC00	21/07/2007	004	017
	ETM+	LE70060142007216EDC00	04/08/2007	006	014
	ETM+	LE70060152006245EDC00	02/09/2006	006	015
	ETM+	LE70070132005217EDC00	05/08/2005	007	013
	ETM+	LE70090112007221EDC00	09/08/2007	009	011
	ETM+	LE70090122007221EDC00	09/08/2007	009	012
	ETM+	LE70110102005229EDC00	17/08/2005	011	010
1999-2001	ETM+	LE70020172000217AGS00	04/08/2000	002	017
	ETM+	LE70040161999212EDC01	31/07/1999	004	016
	ETM+	LE70040171999212EDC01	31/07/1999	004	017
	ETM+	LE70060152001215AGS00	03/08/2001	006	015
	ETM+	LE70070132001190EDC00	09/07/2001	007	013
	ETM+	LE70070142001190EDC00	09/07/2001	007	014
	ETM+	LE70090112001188EDC00	07/07/2001	009	011
	ETM+	LE70090122001188EDC00	07/07/2001	009	012
	ETM+	LE70100102000257SGS00	13/09/2000	010	010
	ETM+	LE70110102000168EDC00	16/06/2000	011	010
1992–1994	TM	LT50020171992219PAC00	06/08/1992	002	017
	TM	LT50040161992217PAC00	04/08/1992	004	016
	TM	LT50040171992217PAC00	04/08/1992	004	017
	TM	LT50050161993242PAC00	30/08/1993	005	016
	TM	LT50060141992263PAC00	19/09/1992	006	014
	TM	LT50060151992263PAC00	19/09/1992	006	015
	TM	LT50080131994170PAC00	19/06/1994	008	013
	TM	LT40090111992212XXX02	30/07/1992	009	011
1985–1988	TM	LT50050161987258XXX01	15/09/1987	005	016
	TM	LT50060141987201XXX08	20/07/1987	006	014
	TM	LT50060151987201XXX08	20/07/1987	006	015
	TM	LT50070131987176XXX01	25/06/1987	007	013
	TM	LT40080121988146XXX01	25/05/1988	008	012
	MSS	LM50090111985248FFF03	05/09/1985	009	011
	MSS	LT40090121988169XXX01	17/06/1988	009	012

were classified using the Normalised Difference Water Index (NDWI) of Huggel et al. (2002), where NDWI = $((B_{NIR} - B_{Blue})/(B_{NIR} + B_{Blue}))$, where B refers to the spectral band. Lakes were automatically identified using an upper threshold of −0.5 and a median filter (3 × 3 kernel) was applied to eradicate erroneously classified and isolated pixels. Each classification was exported as a vector for editing and analysis in ArcMap. Misclassified areas of shadow and cloud were manually identified and removed. Some small lakes that were frozen were manually digitised (~0.5% of all lakes). We limited our subsequent analysis to lakes that were (i) endorheic i.e. without an identifiable outflow, (ii) adjacent to the ice-margin, and (iii) >50,000 m^2 in area. An endorheic condition was imposed to specifically consider meltwater retention.

Each lake was assigned a unique identifier, which we based on latitudinal position. Where a lake split into two discrete water bodies each part was given an additional ‘a’ and ‘b’ identifier. Both absolute (m^2) changes between year groups and relative (%) changes in lake area per year were calculated. Rates of change could not be calculated where imagery was not available in the preceding year group.

The absolute error associated with each measurement of lake area depends on pixel size, the number of pixels forming the lake perimeter and hence on the planform shape of that perimeter. A ‘worst-case’ uncertainty of ±1 pixel around the perimeter of a lake produced a declining power law relationship whereby smaller lakes have the greatest uncertainty associated with their measurement. Lakes ~1 km^2 have a ‘worst-case’ uncertainty of ~7% and lakes of ~5 km^2 are with error 1%.