Changes in the flow pattern of Breiðamerkurjökull reflected by bending of the Esjufjallarönd medial moraine

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Abstract — *The Esjufjallarönd medial moraine separates two branches of the south flowing Breiðamerkurjökull outlet of Vatnajökull ice cap, Southeast-Iceland. The more rapidly flowing easternmost branch (Norðlingalægðarjökull) descends along a trench, reaching 200–300 m beneath sea level, and calves into the Jökulsárlón lagoon. Recently the rate of calving has increased and a depression has formed in the glacier surface. Hence, inflow of ice toward the eastern branch has led to a lateral shift of the Esjufjallarönd medial moraine bending it eastward by up to 900 m, during the period 2006 to 2016. Thus, the moraine has been shifted by ice flow into the lagoon.*

SITE DESCRIPTION

Breiðamerkurjökull is the fourth largest outlet of Vatnajökull ice cap, SE-Iceland. It contains three major ice branches (Mávabyggðarjökull, Esjufjallajökull and Norðlingalægðarjökull) that are separated by two medial moraines named Mávabyggðarönd and Esjufjallarönd (Figure 1), originating from the nunataks Mávabyggðir and the Esjufjöll, respectively.

Norðlingalægðarjökull flows down a 25 km long and 300 m deep subglacial trench (Björnsson *et al.*, 1992; Björnsson, 1996) which may have been excavated by Breiðamerkurjökull during its Little Ice Age advance (until late 19th century), including several surge events (see Pálsson, 1945; Henderson, 1815; Watts, 1962; Thoroddsen, 1931; Thorarinsson, 1943; Sigbjarnarson, 1970; Björnsson, 1998; Björnsson *et al.*, 2003; Björnsson, 2009, 2016). Norðlingalægðarjökull is the fastest flowing branch of Breiðamerkurjökull (Björnsson *et al.*, 2001, Björnsson, 2016, figure 3.14, p. 118). Since the 1890s the withdrawal of Breiðamerkurjökull's margin has been from 33 to 59 m yr^{-1} (Guðmundsson, 2014).

Jökulsárlón lagoon occupies the southernmost part of the subglacial trench. The lake emerged during the rapid retreat of Breiðamerkurjökull in the 1930s and has gradually become larger as the recession has proceeded (Björnsson, 2009). Since the formation of the lagoon the medial moraine has terminated at the west margin of Jökulsárlón. The retreat slowed down from the 1980s until 1995, but has since then been increasing. From 2010–2016 the front retreated by 0.8–1.4 km. The calving front has retreated on the average by 200–280 m yr^{-1} although the downward speed of the ice stream is about 550 m yr^{-1} (Björnsson *et al.*, 2001; Eyjólfur Magnússon, personal communication). A horseshoe-like ice front has been formed in the lake (Figure 2) and a depression in the ice surface upstream from the lagoon has become more and more evident in the 21st century.

The first map showing the Esjufjallarönd medial moraine was surveyed by the Danish General Staff (DGS) in 1904 (Herforingjaráðið 1905). The moraine, however, may have been paid attention to by Gunnlaugsson (1844) when mapping Iceland, as he drew up regional district limits for >13 km upglacier from the Jökulsá river. The medial moraine is located above the western slopes of the trench of Norðlingalægðarjökull, where it slopes into the trench from 20

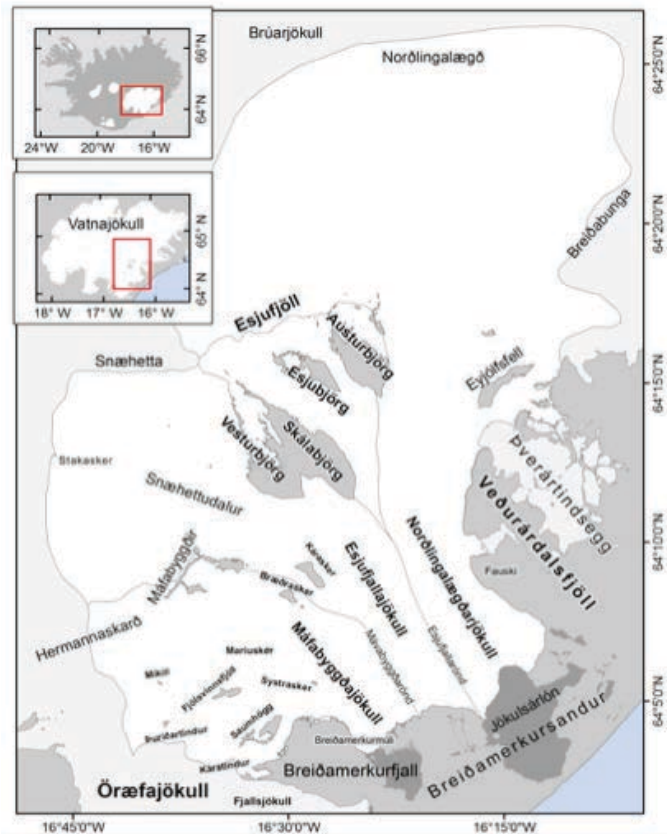

Figure 1. Breiðamerkurjökull outlet glacier of the Vatnajökull ice cap. Surface map based on LiDAR survey in 2010. Ice divides (solid lines) of the three major branches south of the Esjufjöll nunataks are located along the Mávabyggðarönd and Esjufjallarönd medial moraines. Cartography based on Guðmundsson (2014). – *Kort af Breiðamerkurjökli, gert eftir LiDAR mælingum frá 2010.*

to 60 m a.s.l. down to 200 m below sea level over a distance of 1 km. The trench is parallel to the moraine.

In 2014 a peculiar bend on the Esjufjallarönd medial moraine, near and upglacier of the Jökulsárlón lagoon, was detected (Figure 2). This initiated our examination of its development.

MAPPING CHANGES IN THE ESJUFJALLARÖND

We describe changes of the Esjufjallarönd medial moraine by comparision of a high resolution SPOT satellite image of Breiðamerkurjökull, taken in 2004 (SPOT 2004) and a set of georeferenced satellite images from 2006 to 2016 (Landsat 7 and Landsat 8, with pixel resolution of 15–30 m/px., downloaded from the Earth Explorer website http://earthexplorer.usgs.gov/; Figure 4).

As early as 2006 the medial moraine started to be shifted eastward (Figures 3 and 4). In 2007 it, however, became evident that the southernmost tip of the terminus was stagnant where a solid bedrock covered with debris emerged underneath the moraine. The shift varied along the medial moraine, from $\sim$70 m yr^{-1} were it moved at the fastest rate near the lagoon, to $\sim$5 m yr^{-1} about 10 km up from the terminus of the glacier (Figure 5). No translation of the moraine is observed upstream from a subglacial hill, rising above sea level, about 9 km above the calving front (Figure 5). The lower part of the medial moraine has been shifted $\sim$900 m towards east, closest to the lagoon (Figure 3). In 2016 the moraine ended in the lagoon about 0.6–1.0 km above the location of the stagnant moraine piece. The motionless southernmost part of the moraine still contains large amounts of dead ice which will melt over the next years and leave a low ridge of debris.

Figure 2. The Breiðamerkurjökull outlet glacier and Jökulsárlón lagoon, October 10th 2014. In 2015 the Esjufjallarönd medial moraine extended 21 km downglacier from the Esjufjöll nunataks. The peculiar bend is evident west of the calving front of the lagoon. – *Breiðamerkurjökull og Jökulsárlón, 10. október 2014. Esjufjallarönd er urðarrani með upptök í Esjufjöllum. Árið 2015 var lengd urðarranans frá Austurbjörgum 21 km fram á jökulsporð. Sveigjan á röndinni er augljós ofan við Jökulsárlón.* Photo:/*Ljósm.* Snævarr Guðmundsson.

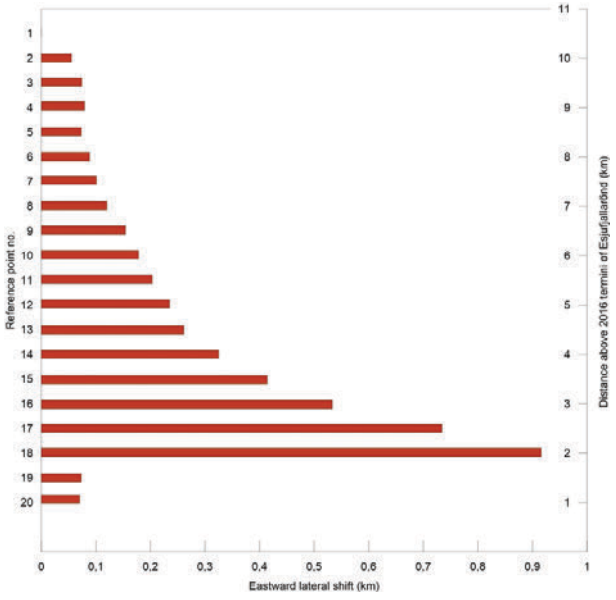

Figure 3. The lateral shift of the Esjufjallarönd medial moraine from 2004 to 2016, along a 10 km long profile from its terminus (right y-axis). The shift was measured perpendicular to the 2004 centerline. – *Hliðrun Esjufjallarandar frá 2004 til 2016, samkvæmt mælingum á 10 km löngu sniði upp frá jökulsporði. Hliðrunin var mæld hornrétt á miðlínu urðarranans.*

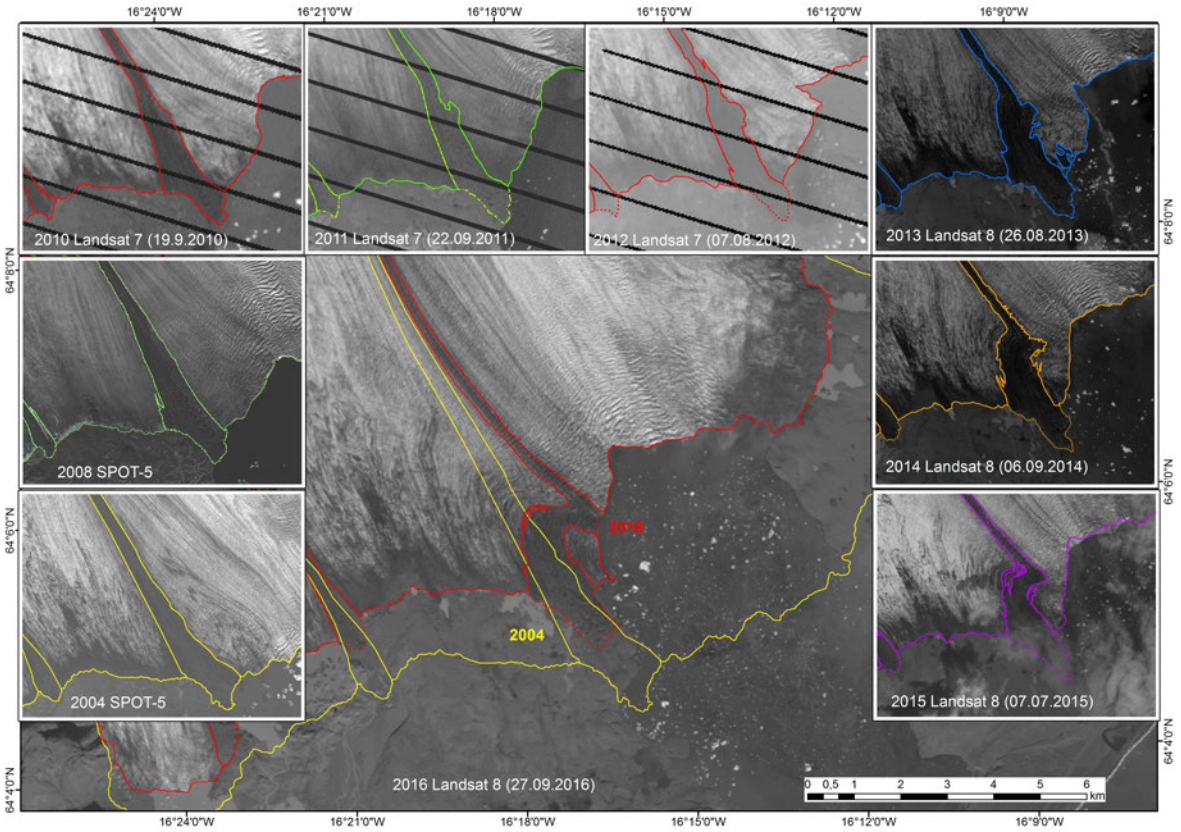

Figure 4. Satellite images showing the evolution of the terminus of Breiðamerkurjökull outlet glacier from 2004–2016 (NASA, 2011–2016). – *Gervitunglamyndir af fremsta hluta Breiðamerkurjökuls frá 2004 til 2016.*

CONCLUSIVE REMARKS

Due to the rapid retreat of Breiðamerkurjökull over the period 2006 to 2016 and the concurrent accelerating growth of the Jökulsárlón lagoon substantial changes of the position of the Esjufjallarönd medial moraine have taken place. The moraine that has separated two ice flow branches of Breiðamerkurjökull has been diverted laterally toward the faster of the two branches indicating a widespread change in the ice flow pattern of Breiðamerkurjökull. Upstream of the calving front at the Jökulsárlón lagoon a horseshoe-like depression has been formed in the glacier surface. This has caused flow of ice from the adjacent glacier branch toward the fast flowing ice stream that occupies a 200–300 m deep and 25 km long trench upstream of the lagoon. The medial moraine used to terminate at the western margin of the lagoon but now it has been directed into the lagoon.

ÁGRIP

Breytingar í flæði Breiðamerkurjökuls mynda hlykk á Esjufjallarönd ofan við Jökulsárlón

Í könnunarflugi yfir Breiðamerkurjökli haustið 2014 sást að hraðar breytingar á jöklinum hafa valdið því að Esjufjallarönd hefur á nokkrum árum sveigst til austurs upp af Jökulsárlóni (2.–5. mynd). Esjufjallarönd er urðarrani sem liggur niður eftir jöklinum frá Esjufjöllum. Röndina myndar bergmulningur sem jöklarnir hafa sorfið úr hlíðum Esjufjalla. Urðarraninn, þ. e. röndin, skilur að Esjufjallajökul (miðarm Breiðamerkurjökuls) og Norðlingalægðarjökul (austurarm-

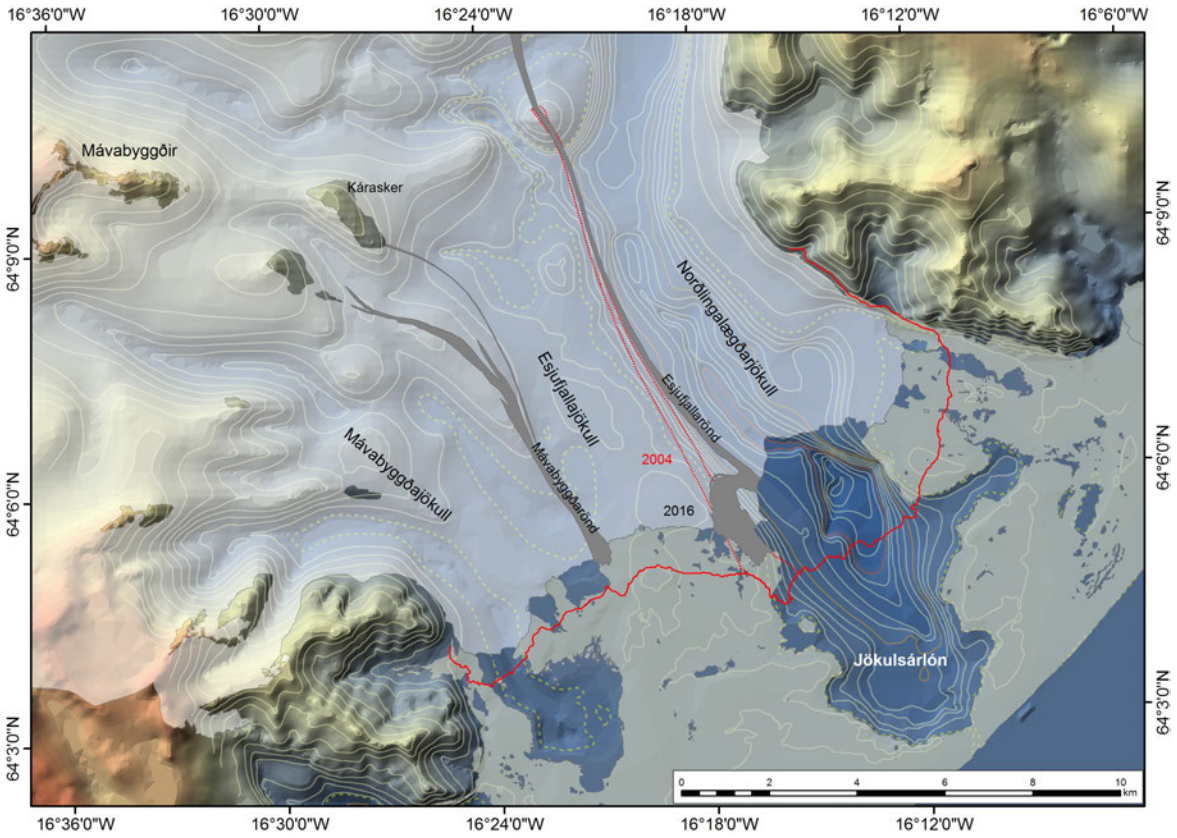

Figure 5. Changes of the terminus of the Breiðamerkurjökull and Esjufjallarönd medial moraines, from 2004 (red line) to 2016. The outlet's surface map is presented with 50% transparency to show the subfloor contours (Björnsson *et al.*, 1992), with 100 m interval but 20 m inside the trench, where Jökulsárlón lagoon is located. Broken lines indicate sea level (0 m). – *Landlíkan af botni Breiðamerkurjökuls. Jökuljaðar, 27. september 2016. Breytingar á sporði Breiðamerkurjökuls og Esjufjallarandar frá 2004 (rauð lína) til 2016. Breiðamerkurjökull er gerður gegnsær til þess að sýna landið undir honum, samkvæmt íssjármælingum Jöklahóps Jarðvísindastofnunar HÍ árið 1991. Renna undir Norðlingalægðarjökli er sýnd með 20 m dýptarbili (gular brotalínur eru 0 m y.s.) en landið ofan sjávarmáls með 100 m hæðarbili. Esjufjallarönd liggur yfir vesturjaðri rennunnar. Fremsti hluti Esjufjallarandar situr nú kyrr á hæð sem rís 20–40 m y.s. Um 9 km norðar fer urðin yfir koll sem rís upp úr jökulbotninum en ofar á jöklinum hefur röndin ekki hliðrast.* Cartography/*Kortagerð* Snævarr Guðmundsson.

inn). Norðlingalægðarjökull skríður niður rennu sem nær 200-300 m niður fyrir sjávarmál og er Jökulsárlón fremsti hluti hennar, en vestan við hana liggur Esjufjallajökull á fremur flötu landi.

Esjufjallarönd hefur lengst af náð fram að vestanverðu Jökulsárlóni eftir að það tók að myndast upp úr 1930, í kjölfar þess að jökullinn tók að hopa. Íssjármælingar sem gerðar voru árið 1991 á Breiðamerkurjökli sýndu að lónið er syðst í mikilli rennu sem nær norður að Esjufjöllum. Varð þá ljóst að við áframhaldandi hop Breiðamerkurjökuls myndi lónið halda áfram að stækka. Jökullinn kelfir (brotnar) í lónið og myndar ísjaka sem eru ferðamönnum á leið um Breiðamerkursand mikið augnayndi.

Eftir 2007 fór að sjást í fast berg fremst við röndina, lónsmegin, og nú virðist fremsti hluti hennar hvíla á þurru landi (4. mynd). Á sama tíma heldur kelfingin áfram og lækkun Norðlingalægðarjökuls upp af

lóninu hefur smám saman valdið því að aukinn hluti Breiðamerkurjökuls hnígur í áttina að Jökulsárlóni. Austurhluti Esjufjallajökuls sækir því inn að dæld upp af lóninu og sveigir um leið röndina austur. Samanburður gervihnattamynda og LiDAR gagna, bendir til að um 2006 hafi Esjufjallarönd verið farin að sveigjast örlítið á 8 km kafla ofan við sporðinn. Sveigjan varð þó fyrst áberandi eftir 2012. Vegna þess að fremsti hluti urðarranans liggur hreyfingarlaus á föstu landi myndast hlykkur á röndina. Hliðrunin á Esjufjallarönd hefur verið að meðaltali 5 m á ári efst á jöklinum og 70 m/ár þar sem hún hefur verið hröðust (3. mynd). Samtímis breikkar röndin, þar sem hraðinn er mestur, hún verður gisnari, sprungur myndast þar sem teygist á jöklinum (2. og 4. mynd).

Esjufjallarönd var farin að brotna fram í lónið vorið 2016 og hafði þá slitið sig frá fremsta hluta randarinnar sem orðinn var kyrrstæður. Enn er mikill ís í fremsta hluta urðarinnar, sem nú er á föstu landi (2016), og mun hann bráðna á nokkrum áratugum og skilja eftir sig hrúgald af urð.

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