Mass balance and precipitation on the summit plateau of Öræfajökull, SE-Iceland

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Abstract — *Measurements of mass balance were made in 1993-1996 and 1997-1998 at 1820 m elevation on the wide summit plateau of Öræfajökull, a large, partly-ice covered strato-volcano on the southeast coast of Iceland. The average winter balance over the period was about 6000 mm and the annual net balance as high as 7780 mm, about double the measured precipitation at the nearby meteorological station of Kvísker. The estimated annual precipitation on the summit plateau of Öræfajökull ranges from 7450 to 7800 mm in the period 1993-1998. Although sparse, the data suggest that in warm summers, ablation and rainfall may lead to several hundred millimeters difference between the net annual mass balance and precipitation. In cool summers the annual net balance is about equal to the annual precipitation. The estimated precipitation values are the highest so far obtained in Iceland.*

INTRODUCTION

Öræfajökull is a strato-volcano on the southeast coast of Iceland and its highest mountain. An ice cap covers the upper part of the mountain and merges to the north with the main part of the Vatnajökull ice cap. The volcano has a wide summit ice-plateau, covering a caldera with a maximum ice thickness of 500 m (Björnsson, 1988). A few nunataks on the caldera rims rise above the summit ice plateau but the caldera rims to the south, west and the southeast are concealed by the ice cover. One of the nunataks is Hvannadalshnúkur, the highest peak in Iceland. The flat summit plateau is 5 km long (N-S) and 3 km wide (E-W) and has an elevation of 1800-1850 m above sea level.

Precipitation in Iceland reaches a maximum in the south and southeast parts (Eythorsson and Sigtryggsson, 1971; Sigfúsdóttir, 1975) with the meteorological station at Kvísker (Figure 1), on the lowland under the eastern slopes of Öræfajökull, having the highest measured precipitation. Thus, the setting of Öræfajökull and its meteorological conditions make it an interesting place to study extremes in precipitation. Moreover, knowledge of the mass balance of its upper parts is important to studies of the behaviour of its outlet glaciers, most of which reach the lowlands. With these aims in mind, annual measurements of mass balance started in 1993, with the support of members of the Iceland Glaciological Society. The results of the work during 1993- 1998 are presented here. The 1993-1996 measurements were reported in Guðmundsson (1995, 1998a, 1998b) and Björnsson *et al.* (1998).

METHODS

The measurement site (63°59.9'N, 16°39.2'W, elevation 1820 m) is located in the centre of the flat summit ice-plateau covering the Öræfajökull caldera. The nunataks closest to the site are about 2 km away and the distance to the plateau edges is nowhere less than 1.5 km, minimizing potential bias due to snowdrift, as often seen close to mountain slopes. The site was visited once each summer, a snow core taken with an engine driven drill and the density of the core measured.

The thickness of the annual layer was determined in a conventional way by defining the previous year's summer surface from changes in grain size and texture of the core. In some cases the uncertainty in the location of the summer surface was 30-50 cm.

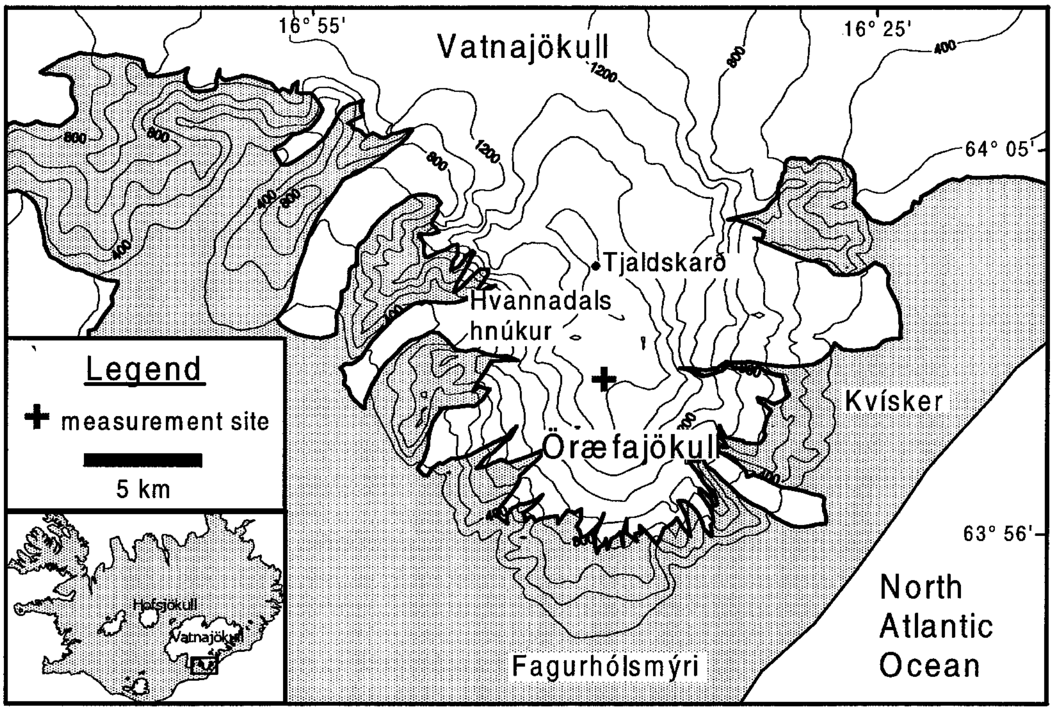

Figure 1. Öræfajökull, location map. The site of measurement in 1993-1998, the meteorological stations of Kvísker and Fagurhólsmýri and the location of the pit dug in 1954 at Tjaldskarð are indicated. – *Öræfajökull. Mælistaðurinn á sléttunni milli Hvannadalshnúks og Hnappa er merktur með krossi. Staðurinn þar sem gryfja var tekin í Tjaldskarði 1954 er merktur með punkti.*

Considering that the thickness of the annual layer is more than 10 metres in all cases, the error in mass balance due to this uncertainty is always less than 5%. Taking other sources of error into account, the error in the measured mass balance is conservatively estimated at about 10%.

MASS BALANCE

The 1993 core was obtained at the end of July, the 1994 core (Figure 2) at the end of August and in 1995, 1996 and 1998 the coring was done in June (Table 1). A pole was left at the measurement site in 1996, and a reading, giving the summer balance, was taken on 1 October.

The June mass balance measurements (1995, 1996 and 1998) give the winter balance at the site while the 1994 measurement, taken at the end of August (roughly the end of the melt season), yields the annual net balance for 1993-1994. The 1993 measurement gives the mass balance for the period September 1992 - July 1993. The annual layer thickness ranges from 10.2 to 13.2 m and the water content from 5750 mm to 7780 mm (Table 1). These values are two to three times higher than reported for other parts of Vatnajökull (Björnsson *et al.*, 1998) and for Hofsjökull in central Iceland (Sigurðsson, 1993). They are also much higher than the 3230 mm obtained on Öræfajökull in 1954 (Rist, 1957) at an elevation of 1810 m.

Table 1. Mass balance at Öræfajökull 1993-1998 and precipitation at Kvísker. *–Afkoma á Öræfajökli 1993-1998 og mæld úrkoma á Kvískerjum.*

year of measurement	date	h m	ρ g/cm^3	b_O mm	P_K mm	b_O/P_K
1993	31.7.	12.0	0.58	6980	3627	1.9
1994	31.8.	13.2	0.59	7780	3538	2.2
1995	12.6.	10.2	0.56	5750	2835	2.0
1996	12.6.	11.7	0.54	6320	2601	2.4
1997	not measured	-	-	-		
1998	14.6.	11.5	(0.54)	(6200)	2959	(2.1)

h: Thickness of annual layer

ρ : Mean density of annual layer

b_O: Mass balance at measurement site (net snow accumulation since about September 1st in previous year).

P_K: Precipitation at Kvísker between September 1st in previous year and measurement date.

Figure 2. The core extracted on 31. August, 1994. Hvannadalshnúkur is in the background. – *Kjarninn sem tekinn var 31. ágúst, 1994. Hvannadalshnúkur í baksýn.*

The pit dug in 1954 was located in Tjaldskarð, a col on the ridge to the north of the caldera (Figure 1). It is likely that high winds in the col cause considerable local snowdrift, reducing the accumulation on the ridge crest. Thus, the accumulation in Tjaldskarð is probably lower than on the summit plateau of Öræfajökull.

The observed net balance at 1820 m on Öræfajökull is about double the measured precipitation at Kvísker and four times that measured at Fagurhólsmýri (Trausti Jónsson, personal comm., 1998). For comparison with the meteorological stations it is assumed here that winter accumulation starts in September. This is reasonable for the highest parts of Vatnajökull, although 1 October may better define the start of the balance year for the lower and medium elevations (Björnsson *et al.* 1998). The ratio of observed mass balance at Öræfajökull and the precipitation at Kvísker (from 1 September in the previous year until the date of measurement at Öræfajökull) varies from 1.9 to 2.4 with a mean of 2.12 (Table 1 and Figure 3).

PRECIPITATION ON ÖRÆFAJÖKULL

It is of some interest to consider how well the observed mass balance values correspond to precipitation and use the data to estimate the annual precipitation on the summit plateau of Öræfajökull. Mass balance data from Vatnajökull (Björnsson *et al.* 1998) suggest that in winter no mass should be lost by melting at 1800 m elevation. However, there are several factors that may bias the measurements. Firstly, snowdrift may cause systematic variations if a net transport of snow occurs from the summit plateau onto the slopes on either side. Secondly, summer ablation may remove mass from the annual layer. Thirdly, some of the summer precipitation may fall as rain and seep through the annual layer. All the above factors would cause the observed mass balance to be lower than the true precipitation.

The significance of snowdrift at the observation site has not been measured but considering that the summit plateau is very flat and has width of a few kilometers, the net removal of snow is probably small. For comparison, Föhn (1980) found that snowdrift-induced variations in snow depth were confined to 200 m wide region on either side of a mountain ridge crest in the Alps.

At an elevation of 1800 m, the summer balance is usually positive on Vatnajökull (Björnsson *et al.*, 1998). Some summer melting usually occurs at 1800 m, however, and occasionally precipitation may fall as rain. Thus, it is to be expected that summer precipitation is greater than summer balance. Loss of mass by summer ablation and seepage through the annual layer is unlikely in 1993 since the lower part of the core was still frozen at the time of measurement. The same applies to the June measurements (1995, 1996 and 1998). In 1994 some mass loss during summer may have occurred. However, the ratio of mass balance at Öræfajökull and the precipitation at Kvísker in 1994 is about the same as for the other years in question, suggesting that possible losses were comparatively small. Moreover, some of the ablation and rainfall in summer refreezes within the annual layer. This can be seen by higher density of the summer/autumn cores which is partly caused by increased thickness and number of ice lenses compared with the spring (June) cores.

Data from 1996 indicate some mass loss by summer ablation and seepage of rain through the annual layer. A stake was left in place in June, and a reading taken on 1 October after an unusually warm September. The stake readings indicate a positive summer balance of 600 mm (water equivalent) while the estimated summer precipitation for 1996 is 1280 mm (Table 2).

In Table 2 an estimate is given for the precipitation on the summit plateau of Öræfajökull between the time of measurement of mass balance and the end of the balance year (September 1st). This period ranges from 0 days (1993-1994) to 80 days (1994-1995 and 1995-1996). The Öræfajökull precipitation is assumed to be 2.12 times the observed precipitation at Kvísker for the same period. Thus, a minimum estimate of the annual precipitation at Öræfajökull is obtained, ranging from 7450 mm (1995-1996) to 7800 mm (1997-1998), similar to the observed annual net balance in 1993-1994.

When compared with other data on precipitation and glacier mass balance in Iceland, the values obtained at Öræfajökull are higher than previously reported. However, the values reported for Mýrdalsjökull in south Iceland are of similar magnitude. Eyþórsson (1945) observed an annual layer thickness of 785 cm at about 1300 m a.s.l. in early August 1944 when melting was well advanced, and Rist (1957) measured a winter balance of 5800 mm at 1350 m a.s.l. in June 1955. These values are only slightly lower than those presented here for Öræfajökull. Thus, it is likely that precipitation at Mýrdalsjökull is similar to that observed at Öræfajökull.

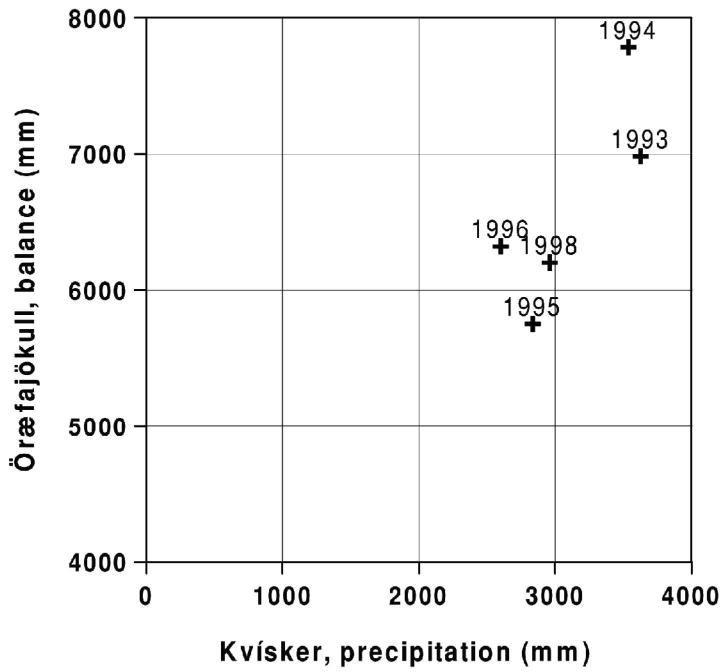

Figure 3. Observed mass balance at Öræfajökull as a function of precipitation at Kvísker 1993-1996 and 1998 (between September 1st in previous year and measurement date). The mean of ratio of the two values is 2.12. – *Tengsl mældrar afkomu á Öræfajökli og úrkomu á Kvískerjum 1993-1996 og 1998. Hlutfall vatnsgildis afkomu á Öræfajökli og úrkomu á Kvískerjum er 2,12.*

Table 2. Precipitation at Kvísker and estimated precipitation at Öræfajökull. –*Úrkoma á Kvískerjum og metin úrkoma á Öræfajökli.*

		Kvísker		Öræfajökull	
balance		no. of	P_{KS}	P_{OS}	P_{OA}
year	dates	days	mm	mm	mm
1992-1993	31.7.93-31.8.93	31	276	590	7570
1993-1994	31.8.94-31.8.94	0	0	0	7780
1994-1995	12.6.95-31.8.95	80	801	1700	7450
1995-1996	12.6.96-31.8.96	80	603	1280	7600
1997-1998	14.6.98-31.8.98	78	756	1600	7800

P_{KS}: Precipitation at Kvísker between the dates given.
P_{OS}: estimated precipitation at Öræfajökull between the dates given, $P_O = 2.12\ P_{KS}$ where 2.12 is the mean of the ratio of balance at Öræfajökull and precipitation at Kvísker.
P_{OA}: estimate of annual precipitation at Öræfajökull, $P_{OA} = b_O + P_{OS}$, (b_O is given in Table 1).

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The fieldwork was mainly done by volunteers of the Iceland Glaciological Society during expeditions to Vatnajökull in 1995, 1996 and 1998. The trips in 1993 and 1994 were made possible by the participation and contributions of volunteers, especially Halldór Gíslason, Þorsteinn Jónsson, Garðar Briem, Birgir Vagnsson, Árni Páll Árnason and Jón Sigþórsson. Trausti Jónsson at the Iceland Meteorological Office kindly made available data on precipitation at Kvísker and Fagurhólsmýri. Helgi Björnsson provided helpful comments on an early draft and reviews by Bryndís Brandsdóttir and an anonymous reviewer improved the quality of this paper. Þórdís Högnadóttir and Finnur Pálsson are thanked for assistance and support.

ÁGRIP

ÁKOMA OG ÚRKOMA Á ÖRÆFAJÖKLI

Afkoma á Öræfajökli, í 1820 m hæð á sléttunni milli Hvannadalshnúks og Hnappa (63°59.9'N, 16°39.2'V), var mæld fimm sinnum í ferðum á vegum Jöklarannsóknafélags Íslands á árunum 1993-1998 (1. mynd). Boruð var kjarnahola gegnum árlagið, kjarninn veginn og vatnsgildið þannig mælt. Mælt var einu sinni á ári, en mælingarnar voru ekki allar gerðar á sama tíma. Þrjár voru gerðar í júní (1995, 1996 og 1998), ein í lok júlí (1993) og ein í lok ágúst (1994). Mælingarnar sýna því afkomu fyrir tímabilið frá u.þ.b. 1. september árið áður og fram til mælidags. Snjólag ársins var á bilinu 10,2 til 13,2 m og vatnsgildi 5750-7780 mm (1. tafla). Í einu tilviki (1994) er um afkomu heils árs að ræða, í þremur tilvikum vetrarafkomu (1995-1998) og í einu tilviki vetrarafkomu og hluta sumarafkomu (1993). Mælingarnar benda til að öll vetarúrkoma falli sem snjór og mestur hluti sumarúrkomunnar einnig. Til þess að meta ársúrkomu efst á Öræfajökli, voru afkomumælingarnar bornar saman við mælda úrkomu á Kvískerjum og Fagurhólsmýri. Í ljós kemur að fyrir þau ár sem mælingarnar ná yfir er vatnsgildi snjósöfnunar á Öræfajökli að meðaltali 2,12 sinnum meira en úrkoma á Kvískerjum. Þessi stuðull er notaður til að áætla úrkomu á Öræfajökli milli þess tíma sem mæling er gerð að vori eða sumri, og þar til vetrarsnjór fer aftur að safnast á jökulinn (nálægt mánaðarmótum ágúst og september). Að lokum er ársúrkoma á Öræfajökli áætluð með því að leggja saman mælda afkomu (frá u.þ.b. 1. september til mælidags) og reiknaða úrkomu (frá mælidegi til loka ágústmánaðar). Niðurstöðurnar eru í 2. töflu og benda til að fyrir þau ár sem mælingarnar ná yfir hafi úrkoma á jökulinn í öskju Öræfajökuls jafngilt 7450-7800 m af vatni. Þetta er mesta úrkoma sem vitað er um á Íslandi og þar sem mjög lítill hluti hennar bráðnar á staðnum, er afkoman sú langhæsta fyrir íslenska jökla. Niðurstöðurnar benda til að úrkoman sé tvöfalt til þrefalt meiri á Öræfajökli en algengast er á Vatnajökli og Hofsjökli. Þær afkomumælingar sem til eru frá Mýrdalsjökli benda til ívið lægri úrkomu en á Öræfajökli. Munurinn er þó varla marktækur og má telja víst að þessir tveir staðir séu þeir úrkomusömustu á landinu.

REFERENCES

Björnsson, H. 1988. Hydrology of ice caps in volcanic regions. *Soc. Sci. Islandica*. 45, Reykjavík, 139 pp.

Björnsson, H., F. Pálsson, M.T. Guðmundsson and H.H. Haraldsson 1998. Mass balance of western and northern Vatnajökull, Iceland, 1991-1995. *Jökull* 45, 35-58.

Eythorsson, J., and H. Sigtryggsson 1971. The climate and weather of Iceland. *The Zoology of Iceland* 1, (3), 1-62.

Eyþórsson, J. 1945. Um Kötlugjá og Mýrdalsjökul. *Náttúrufræðingurinn* 15, 145-174.

Föhn, P.M.B. 1980. Snow transport over mountain crests. *Journal of Glaciology* 26, 469-480.

Guðmundsson, M.T. 1995. Vorferð JÖRFI 1993. *Jökull* 43, 80-81.

Guðmundsson, M.T. 1998a. Vorferð JÖRFI 1995. *Jökull* 45, 95-96.

Guðmundsson, M.T. 1998b. Vorferð JÖRFI 1996. *Jökull* 46, 69-70.

Rist, S. 1957. Snjómæling á jöklum 1954 og 1955. *Jökull* 7, 33-36.

Sigfúsdóttir, A.B. 1975. Úrkoman á Vatnajökli. *Veðrið* 19, 46-47.

Sigurðsson, O. 1993. Afkoma nokkurra jökla á Íslandi 1989-1992. *Orkustofnun, OS-93032/VOD-02*, 26 pp.