ICE CAULDRONS IN THE KATLA CALDERA: DATA ON TEMPORAL VARIATIONS FROM AIRBORNE GROUND CLEARANCE RADAR

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1. Introduction

Since October 1999, profiles of ice surface elevation within the Katla caldera have been surveyed on a regular basis. The purpose of these surveys is to monitor changes in geothermal activity and possible subglacial water accumulation. These profiles cross the 17 identified ice cauldrons caused by geothermal activity underneath the ice (Figure 1 and Table 2). The profiling is done from aircraft using a system consisting of a ground clearance radar, kinematic GPS (KGPS) and a laptop PC. Surveying is now done twice a year, in spring and autumn. The aircraft of the Icelandic Civil Aviation Administration (Beech King Air B200) is used for the surveying.

In this report the surveying and data processing is briefly described, a sample data file explained and the results presented in profile form. The profiles are also available at the web-page of the Institute of Earth Sciences: http://www.earthice.hi.is. The direct path to the Katla monitoring page is: http://www.earthice.hi.is/page/iesmysurv.

2. Surveying system

The following description is mainly an extract from Gudmundsson et al. (in press):

The radar altimeter is an analog Collins ALT-50, operating at 4300 MHz with an error of 2%. This radar altimeter was already installed in the aircraft and used as a low altitude elevation monitoring and terrain warning system and faces directly downwards. Dynamic range of the altimeter is 0-995 meters of height. Beamwidth is around 20° of a conical shape. Therefore in order to keep horisontal resolution and vertical accuracy within reasonable limits, the aircraft is flown at 70-100 m above the glacier surface. The altitude measured by the radar is corrected in software with two linear functions of the first order. These linear models were developed on data derived from an airborne data adjustment campaign with test flights over sea, land and icy surfaces. The radar footprint is a circle of around 15 m radius for these nominal altitudes and the radar measures in general the first viable response (the highest ground). In this respect it can be theorized that limit of horizontal radar resolution of the first response can be determined from the width of the first Fresnel zone (d), given by $d = (h\lambda/2)^{1/2}$, where h is height above the target (glacier surface) and $\lambda = 7$ cm is the wavelength in question. For our nominal flying heights this would then be a footprint of d = 3.5-4 m. And thus, the accuracy of the aeroplane height relative to the glacier surface is about 2 m when flying in the expected areas of low surface sloping. Actual measurements confirm this theory as is described below. The accuracy of the kinematic GPS is estimated within 1 m, yielding a total estimated error in measured height of around 2-3 m for the baseline lengths in question. The surveys are conducted using the WGS84 geodetic reference system and the NKG96 geoid for conversion of GPS-derived height above ellipsoid to height above sea level. The reference station is usually set up in Reykjavik which is some 150-200 km away from the areas of interest and the manufacturer of the GPS system used, gives accuracy error of 1mm+1PPM (parts per million) per given baseline resulting in around

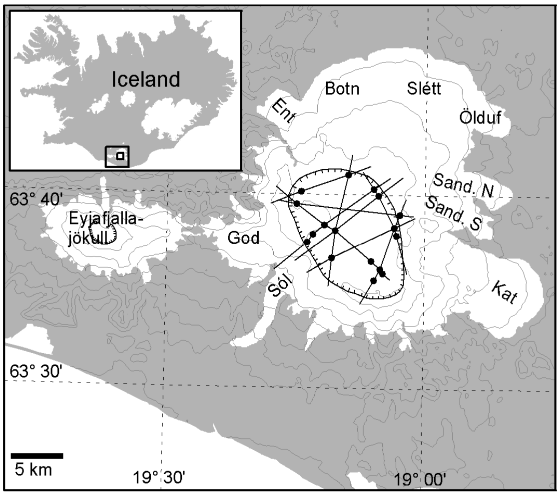

Figure 1a. Eyjafjallajökull and Katla. Ice surface profiles surveyed 1999-2006.

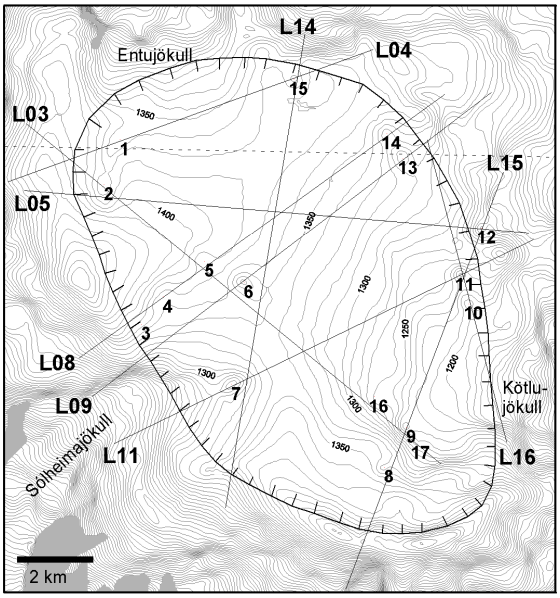

Figure 1b. Profile location 8 October - 5 November 1999 (see coordinates in Table 2a).

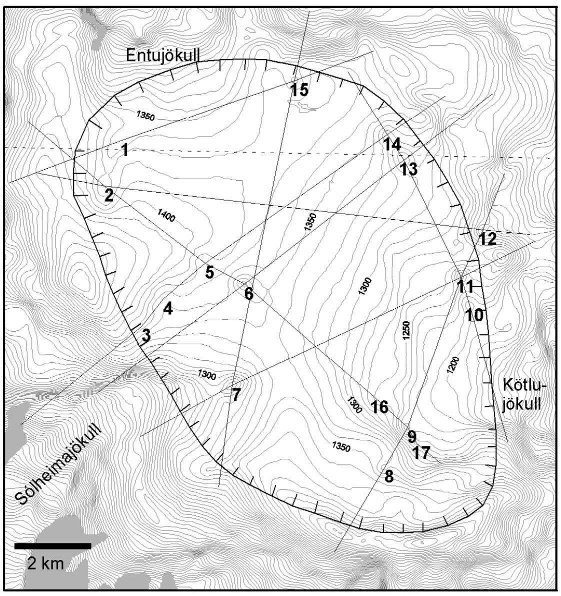

Figure 1c. Profiles flown since 27 November 1999 (See coordinates in Table 2b).

20 cm theoretical accuracy. On the other hand the baseline lengths cause an increase in error because of different view to satellites in the GPS constellation resulting in the aforementioned accuracy estimate of just under 1m. The GPS gives a position once every second, while the ground clearance is measured 4 times a second. Typical aircraft velocity is 70-80 m s^{-1} implying that a sounding of the glacier surface occurs at 17-20 m intervals along the flightline. Accurate time based on GPS satellite constellation time from the GPS receiver together with the altimeter readings (digitised through an AD converter), are sampled on to a laptop PC. After post-processing of the GPS positions, the coordinates of the three intermediate elevation sounding points are obtained by linear interpolation of the 1 second GPS coordinates.

The internal consistency of the airborne elevation soundings was tested with analysis of the mis-tie in 54 crossover points on Mýrdalsjökull. The mean waypoint error obtained was 1.2 m. Traverses of the same lines between waypoints with the airborne radar altimeter system have been compared to DGPS positions collected by a snowmobile traveling the same lines on the glacier surface in September 2000 (Fig. 4 in Gudmundsson et al., in press). The Trimble Pathfinder submeter DGPS system used for the snowmobile traverses has been shown to yield horizontal error less than 1 m and vertical error less than 2 m for the baseline lengths of 50-100 km, as used for this survey (Gudmundsson et al., 2002). The results show that where the flightline and the snowmobile track coincide, the standard deviation of the difference between the two elevations is 0.9 m. Thus, provided aircraft height above ground is not significantly greater than 100 m we conclude that the system has an absolute accuracy cautiously estimated as 3 m, and an internal consistency of 1-2 m. This accuracy is achieved in calm weather with good visibility. If surveying is carried out under windy conditions, irregular tilting of the aircraft will lead to deviations from the vertical and increased pilot corrections to the aircraft flight cause more noisy data. Relatively calm days are therefore selected for surveying to match better with the test set used to authenticate the relative accuracy of the method.

3. Data processing

KGPS data and radar altimeter altitudes are processed by the Civil Aviation Administration. These raw results come in two files:

a) The coordinate file (*.cor) contains the following information at 1 sec. intervals:

- time (in seconds)
- latitude
- longitude
- ground clearance (in m)
- Flight elevation (in m above ellipsoid)
- Ground elevation (m a.e.)

b) The elevation file (*.log) contains information on ground clearance (sampling interval 0.25 s):

- date
- time (hours:min:sec)
- four ground clearance measurements (4 measurements/sec.)

The processing done at IES:

- check of consistency of data files
- merging of the *.cor and *.log files into a single data file with elevation at 0.25 sec. intervals.
- A step in the above is the calculation by interpolation of the coordinates of the three fraction-of-a second elevation sounding points.
- Random noice of amplitude <1 m is present in the 0.25 sec. data. This noice is partly removed by running a smoothing filter (usually 5 point weighted average, but occasionally a 5 point moving average is applied).
- Gaps of 1-4 seconds sometimes occur in the GPS data. Each such gap is inspected and the missing coordinates estimated by interpolation. Gaps of this type do not occur on all flights and their existence has a very minor effect on the integrity of the data, since gaps in ground clearance radar data hardly ever occur.
- Coordinate transformation from WGS874 to ISN93 coordinates.
- subtraction of geoid height from ellipsoid heights.
- Subtraction of a 2.5 m from the derived elevation. This correction was obtained by comparison with ground-based elevation determinations.
- The data-file for the flight is split into individual profile-files.

Finally, the data are displayed in profile form. Because of the combined effects of summer ablation and ice flow, the glacier surface is systematically lower in autumn than in spring. Thus, autumn flights and spring flights are displayed seperately (http://www.earthice.hi.is/page/iesmysurv).

An overview of survey flights 1999-2006 is given in Table 3.

4. Results

An example of a processed data file is shown on Table 4. The profiles for 1999-2006 are displayed on the following pages. For interpretation the reader is referred to Gudmundsson et al. (in press).

The profile files (Table 4) have names based on the line number and the month that the flight took place, i.e:
L03-0004.dat: Line 3, year 2000, month: April. Date in Table 3.
L16-0511.dat: Line 16, year 2005, month: November. Date in Table 3.
Exceptions to this naming convention occur in October and November 1999, when two flight were flown in the same month. Then the file name also includes the date, i.e.
L03-991016.dat – was flown on 16 October 1999.

The data files are available to VOLUME members when requested.
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Table 1. Cauldron coordinates.

Cauldron	Lat, Long	X, Y (ISN93)
01	63.66893, 19.24096	488068, 351630
02	63.65823, 19.24900	487665, 350439
03	63.62548, 19.22773	488705, 346784
04	63.63200, 19.21643	489268, 347509
05	63.64060, 19.19475	490346, 348464
06	63.63580, 19.17377	491384, 347926
07	63.61176, 19.17918	491109, 345247
08	63.59291, 19.09767	495150, 343135
09	63.60246, 19.08611	495725, 344200
10	63.63167, 19.05427	497309, 347455
11	63.63836, 19.05906	497072, 348201
12	63.64956, 19.04802	497620, 349450
13	63.66568, 19.09042	495522, 351248
14	63.67151, 19.09943	495076, 351899
15	63.68390, 19.14917	492616, 353285
16	63.60942, 19.10358	494859, 344978
17	63.59865, 19.08100	495978, 343775

Table 2a. Flight line coordinates 08.10.1999-05.11.1999.

Line	Coordinates of starting point		Flight direction	Couldrons crossed
	Lat, Long	X, Y (ISN93)		
L-03	63.67218, 19.29066	485610, 352005	NW/SE/SE	2, 5, (6), 9
L-04	63.65852, 19.29965	485155, 350485	WSW	1, 15
L-05	63.65646, 19.29125	485570, 350250	E	2, 12
L-08	63.61718, 19.26040	487080, 345865	NE/NE/SW	5, 14
L-09	63.60820, 19.25303	487445, 344865	SW	6, 13
L-11	63.59732, 19.24070	488050, 343645	NE/SW/NE	7, 11
L-14	63.69452, 19.14395	492880, 354490	NNE	6, 7, 15
L-15	63.56405, 19.11680	494195, 339920	SSW/NNE/NNE	8, 9, 11, 12
L-16	63.68525, 19.07732	496175, 353430	NNW/SSE/SSE	10, 11, 14

Table 2b. Flight line coordinates 27.11.1999 and onwards.

Line	Coordinates of starting point		Flight direction	Couldrons crossed
	Lat, Long	X, Y (ISN93)		
L-03	63.67296, 19.29003	485640, 352090	SE	2, 5, 6, 9, 16, 17
L-04	63.65852, 19.29965	485155, 350480	ENE	1, 15
L-05	63.66100, 19.28470	485900, 350755	W	2, 12
L-08	63.60145, 19.29075	485570, 344120	NE	3, 4, 5, 14
L-09	63.60919, 19.25128	487530, 344970	SW	6, 13
L-11	63.59911, 19.22742	488710, 343845	SW	7, 11
L-14	63.70025, 19.14184	492985, 355110	SSW	6, 7, 15
L-15	63.57243, 19.12356	493860, 340855	NNE	8, 9, 11, 12
L-16	63.68622, 19.12090	494015, 353540	NNW	10, 11, 13, 14

Table 3. Overview of survey flights

Date	Number of lines in caldera	Elevation accuracy (m)	Comments
991008	17	2	+ lines down outlet glaciers: Sól, Kat. and Ent.
991016	9	2	Reduced set of lines - used hereafter for caldera
991105	9	2	
991127	9	2	Improved survey lines – hereafter crossing centres of all cauldrons
991217	9	2	
000127	10	2	New line flown within caldera
000413	9	2	
000710	9	3-4	Flown at slightly higher elev. + 2 lines down Sól.
000914	9	2	
001104	9	2-5	+ line down Sól.
010531	10	2	Sampl. int. 1 sec. – line 6 from 991008 flown also
011024	9	2	
020516	9	2	
021027	9	2	
030513	9	2	+ lines down Sól., Kat. and Ent.
031008	9	2	
040716	9	2	
041007	9	2	+ lines down Sól., Kat., Ent., Slétt. and God.
050518	9	2	+ lines down Kat., Slétt., Botn., Ölduf., Sand. N, Sand. S
051112	9	2	+ lines down Sól., Kat., Ent., Slétt. and Godj.
060427	9	2	+ lines down Kötluj., Ent. and Sléttj.

Abbrevations for outlet glaciers/areas outside caldera:

Sól: Sólheimajökull (southwest part)
Kat: Kötlujökull (eastern part)
Ent: Entujökull (northern part)
Slétt: Sléttjökull (northern part)
God: Goðalandsjökull (southwest part)
Sand. N: Northern Sandfellsjökull (eastern part)
Sand. S: Southern Sandfelljökull (eastern part)
Ölduf: Öldufellsjökull (northeast part)

Table 4. Example of profile data

Latitude (°N)	Longitude (°W)	ISN93 X (m)	ISN93 Y (m)	H_s (m)	ΔZ (m)	N (m)	time (sec.)	length (km)
63.590020	19.060511	496995.16	342811.94	1341.83	110.80	66.83	34510.00	14.573
63.590112	19.060777	496981.94	342822.22	1341.39	110.85	66.83	34510.25	14.557
63.590204	19.061044	496968.69	342832.53	1340.85	110.99	66.83	34510.50	14.540
63.590297	19.061310	496955.47	342842.81	1340.60	110.85	66.83	34510.75	14.523
63.590389	19.061577	496942.25	342853.13	1339.87	111.19	66.83	34511.00	14.506
63.590483	19.061841	496929.16	342863.66	1339.24	111.63	66.84	34511.25	14.489
63.590577	19.062105	496916.03	342874.16	1338.33	112.36	66.84	34511.50	14.473
63.590672	19.062369	496902.94	342884.69	1338.29	112.21	66.84	34511.75	14.456
63.590766	19.062633	496889.84	342895.19	1337.51	112.80	66.84	34512.00	14.439
63.590862	19.062895	496876.84	342905.91	1336.86	113.48	66.84	34512.25	14.422
63.590958	19.063156	496863.88	342916.63	1335.14	115.24	66.84	34512.50	14.405
63.591054	19.063418	496850.91	342927.34	1335.27	115.14	66.84	34512.75	14.389
63.591150	19.063679	496837.94	342938.06	1334.28	116.17	66.84	34513.00	14.372
63.591247	19.063939	496825.06	342948.91	1333.72	116.95	66.84	34513.25	14.355
63.591344	19.064198	496812.22	342959.75	1331.69	119.19	66.84	34513.50	14.338
63.591441	19.064457	496799.34	342970.59	1332.16	118.95	66.84	34513.75	14.321
63.591538	19.064717	496786.47	342981.44	1330.72	120.61	66.84	34514.00	14.304
63.591636	19.064975	496773.69	342992.34	1329.19	122.51	66.84	34514.25	14.288
63.591734	19.065232	496760.88	343003.25	1326.04	126.03	66.84	34514.50	14.271
63.591832	19.065490	496748.09	343014.16	1327.20	125.25	66.85	34514.75	14.254

H_s: Height above sea level
ΔZ: Aircraft height above glacier surface
N: Geoid height
length: Distance along profile from starting point (Table 2)

5. References

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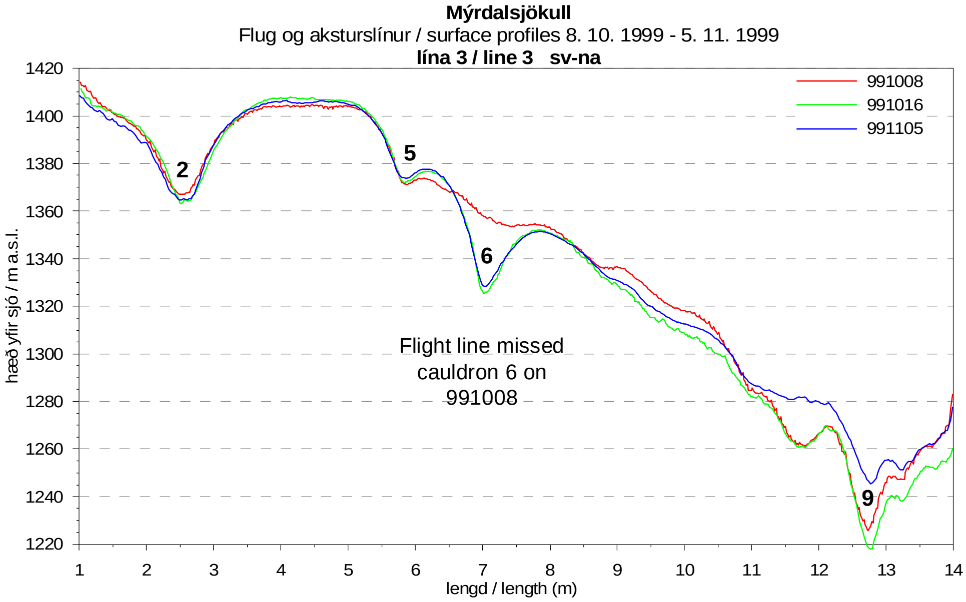
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2
5
6
9
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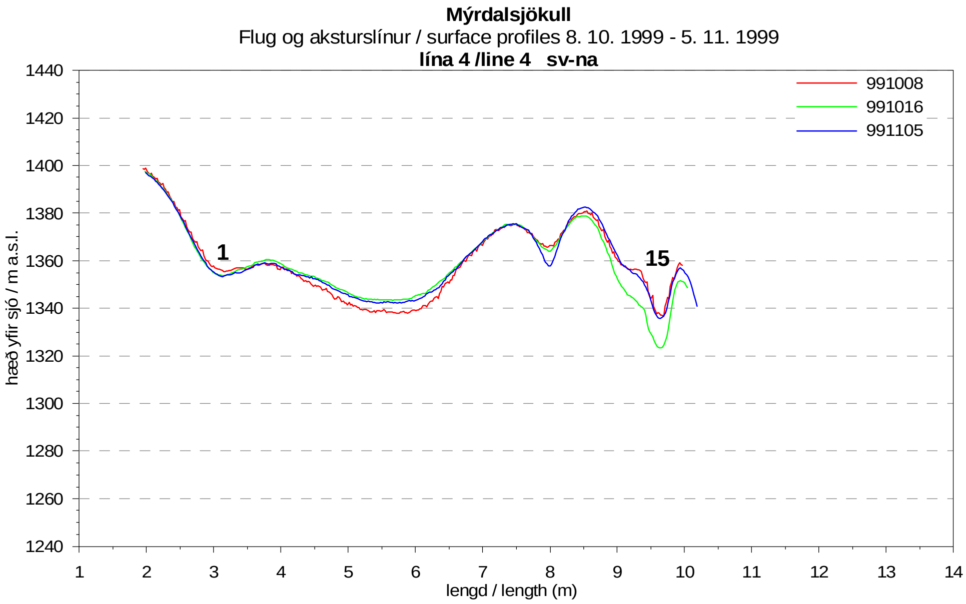
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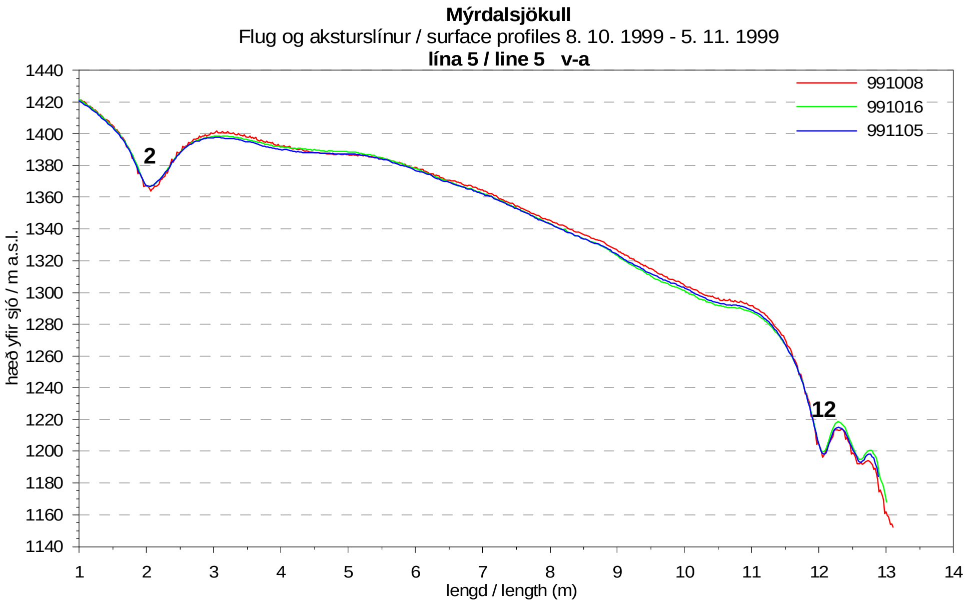
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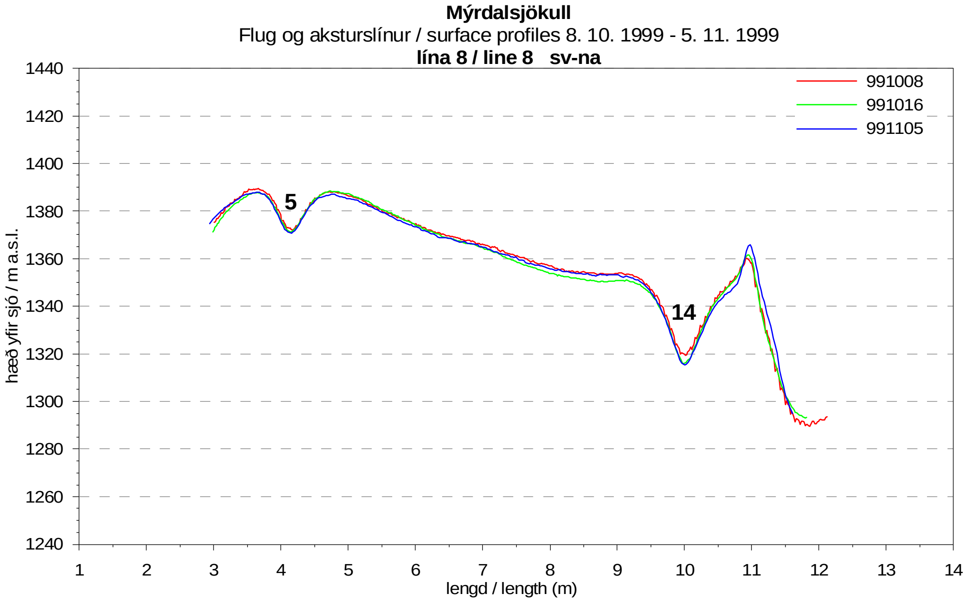

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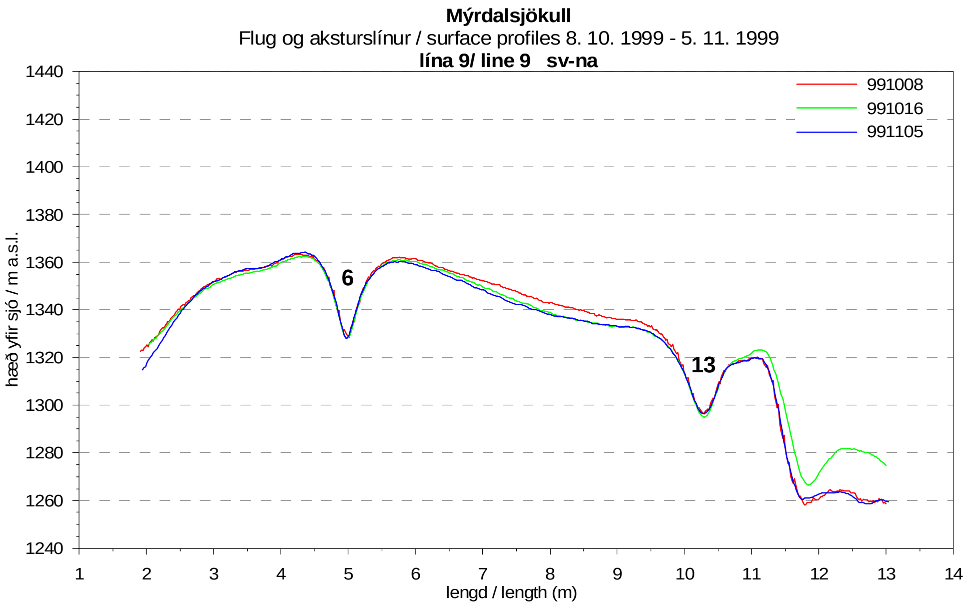

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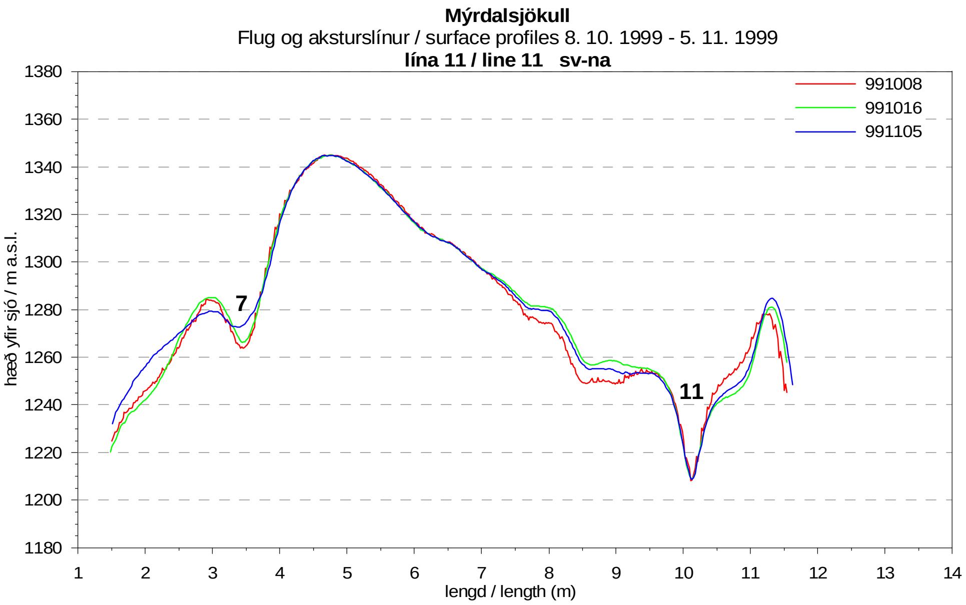

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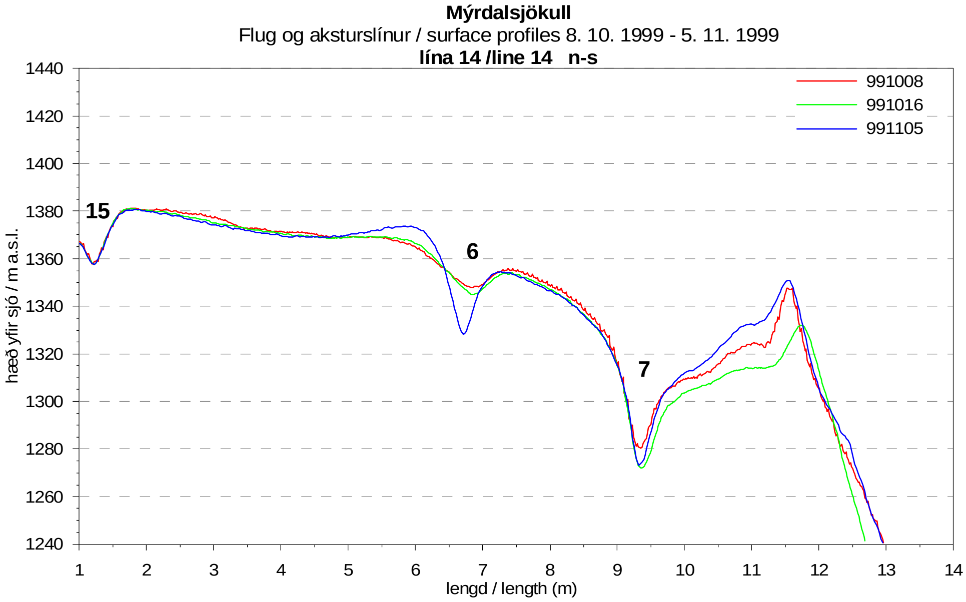
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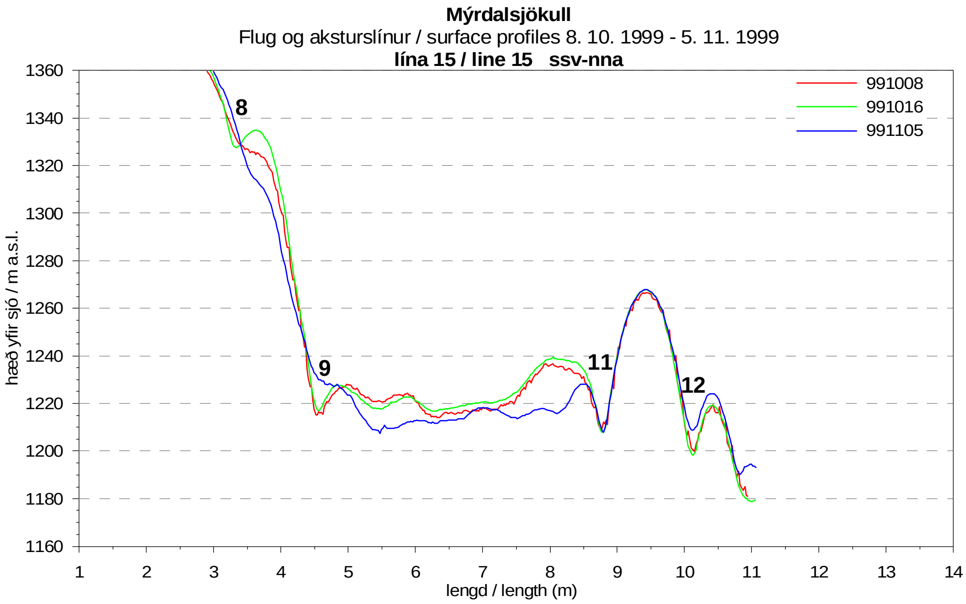
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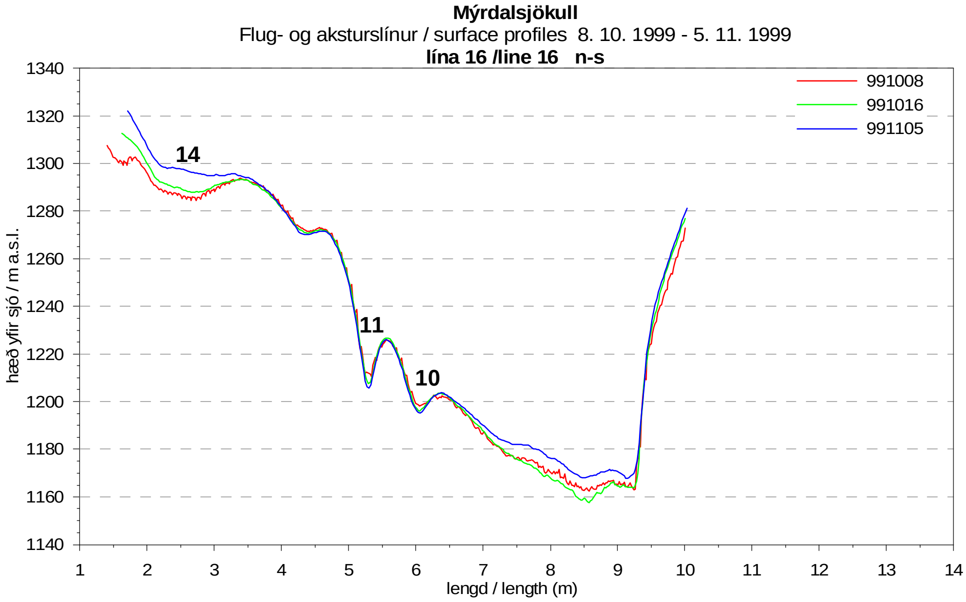
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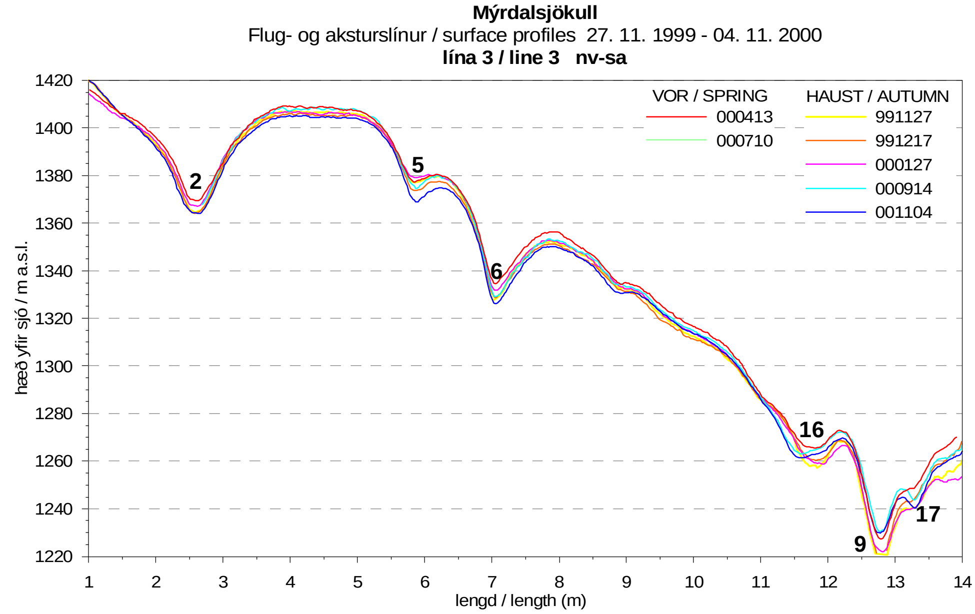
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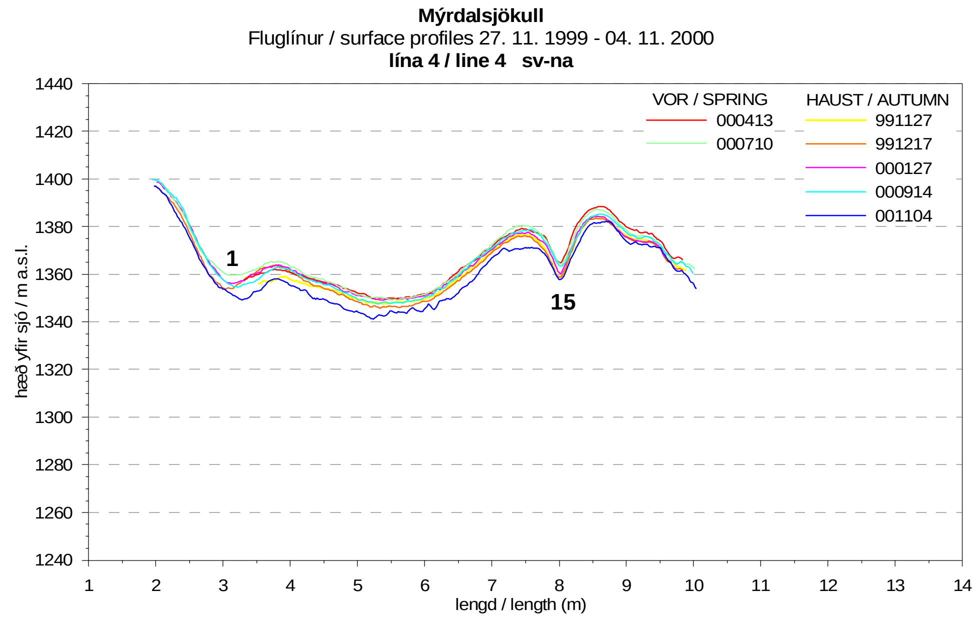
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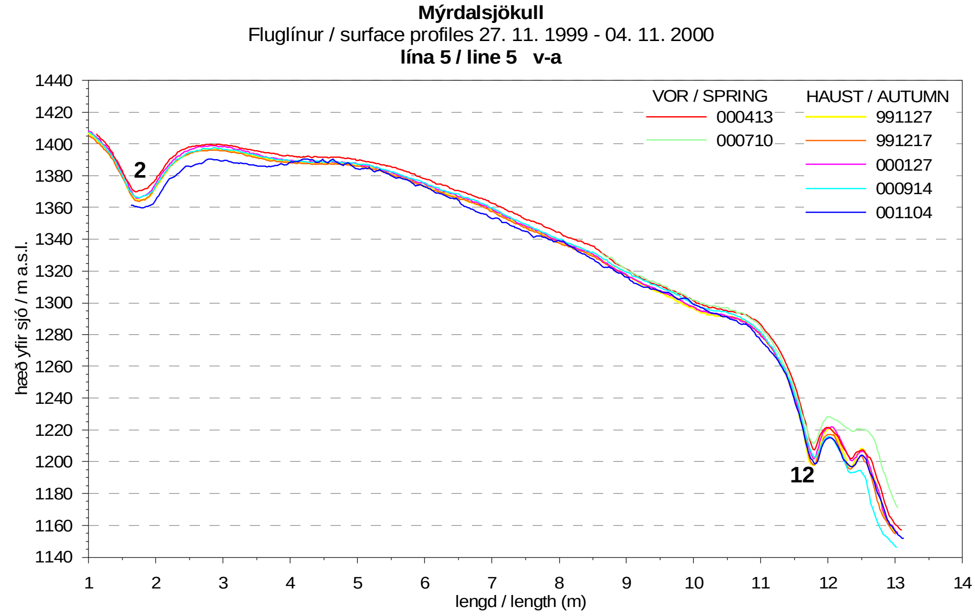
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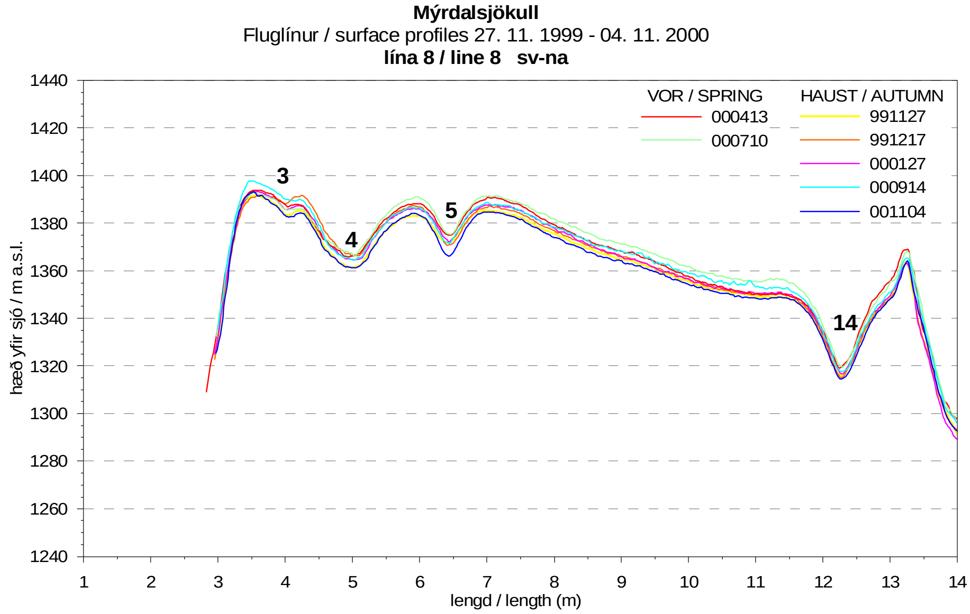
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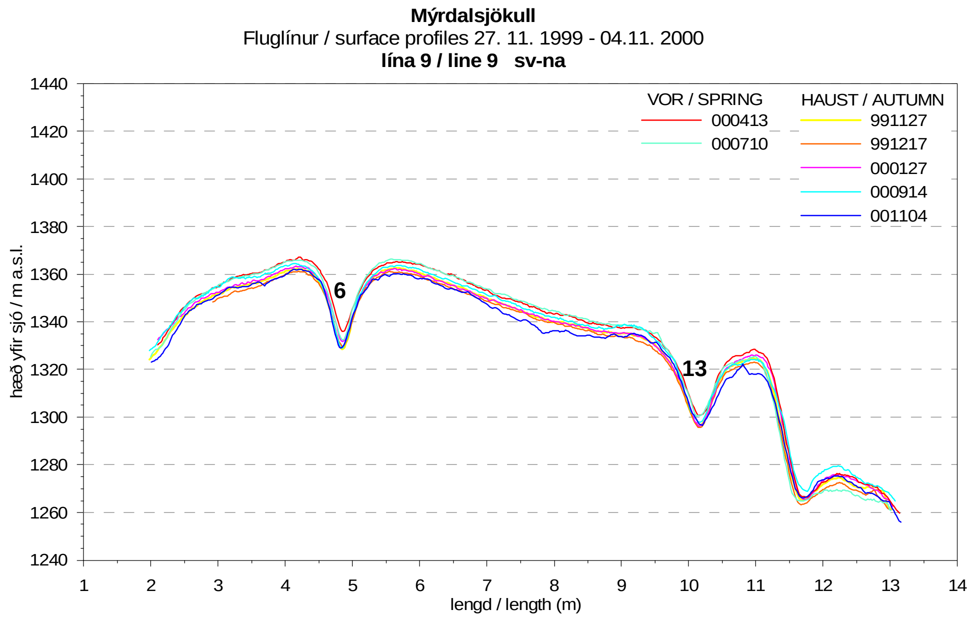
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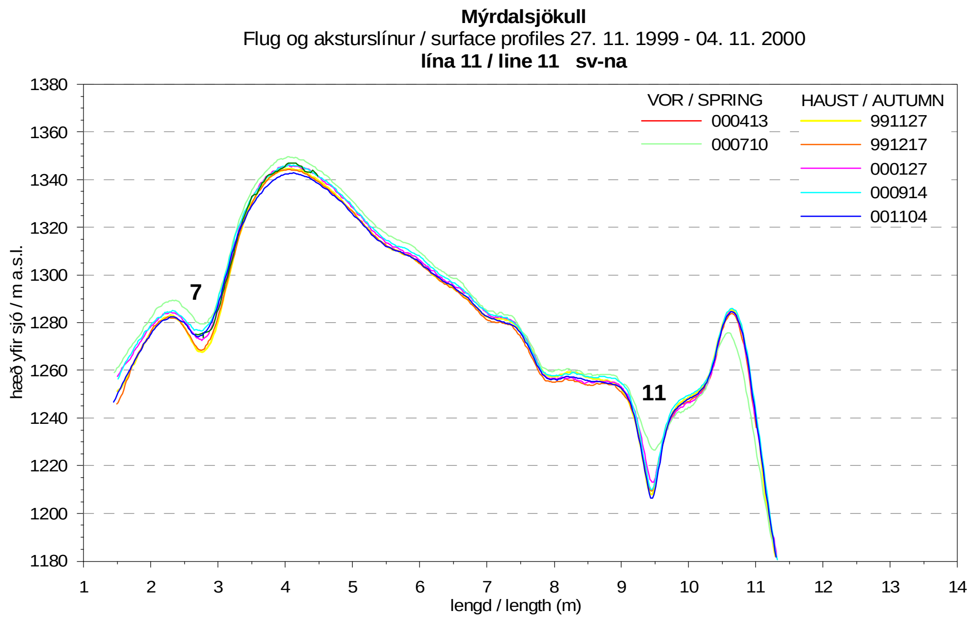
lína 9 / line 9 sv-na
VOR / SPRING
000413
000710
HAUST / AUTUMN
991127
991217
000127
000914
001104
6
13
hæð yfir sjó / m a.s.l.
lengd / length (m)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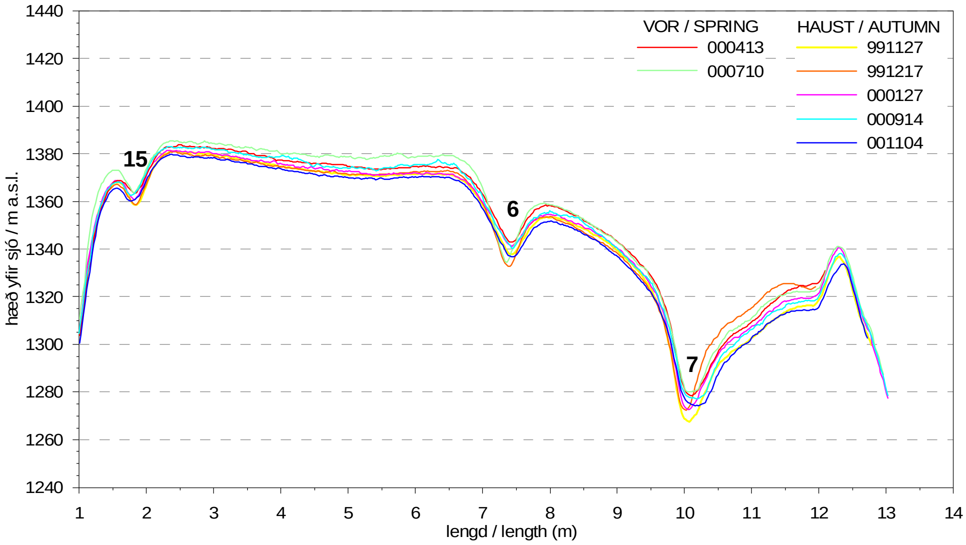
Flug og aksturslínur / surface profiles 27. 11. 1999 - 04. 11. 2000
lína 11 / line 11 sv-na
VOR / SPRING
000413
000710
HAUST / AUTUMN
991127
991217
000127
000914
001104
7
11
hæð yfir sjó / m a.s.l.
lengd / length (m)

Mýrdalsjökull
Fluglínur / surface profiles 27. 11. 1999 - 04. 11. 2000
lína 14 / line 14   n-s



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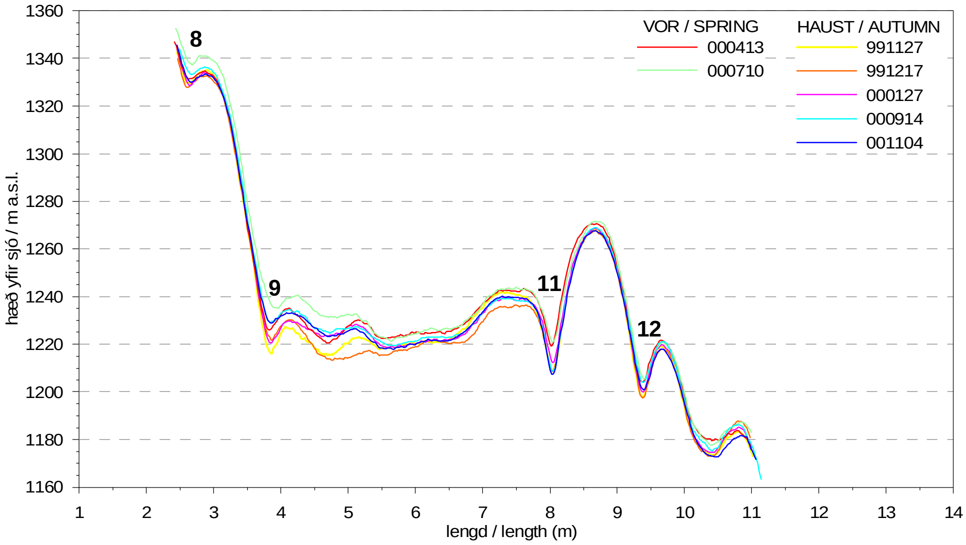
Flug- og aksturslínur / surface profiles 27. 11. 1999 - 04. 11. 2000
lína 15 / line 15   ssv-nna



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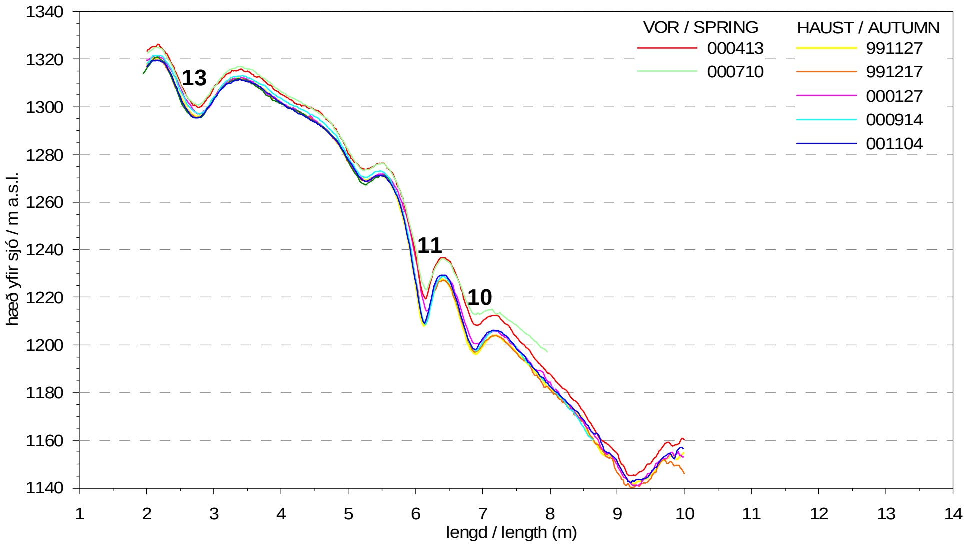
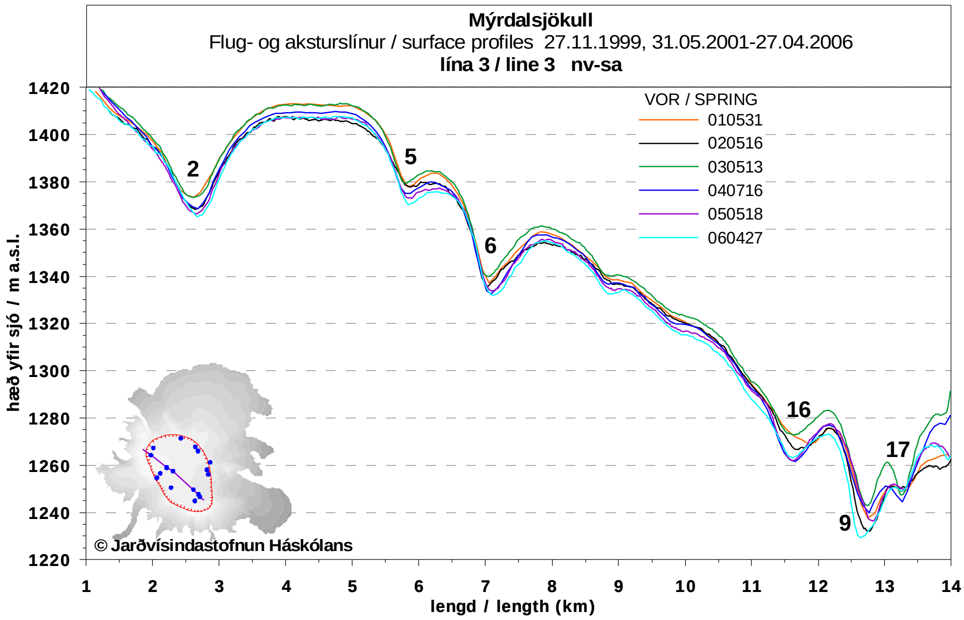
Flug- og aksturslínur / surface profiles 27. 11. 1999 - 04. 11. 2000
lína 16 / line 16   n-s




Mýrdalsjökull
Flug- og aksturslínur / surface profiles 27.11.1999, 31.05.2001-27.04.2006
lína 3 / line 3 nv-sa
VOR / SPRING
010531
020516
030513
040716
050518
060427
hæð yfir sjó / m a.s.l.
lengd / length (km)
2
5
6
16
17
9
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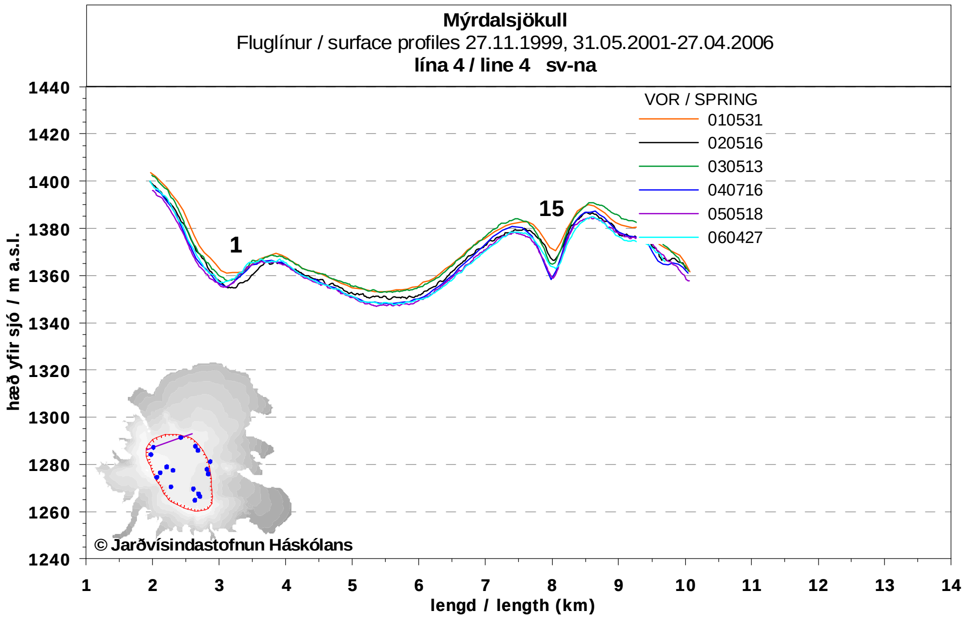
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Fluglínur / surface profiles 27.11.1999, 31.05.2001-27.04.2006
lína 4 / line 4 sv-na
VOR / SPRING
010531
020516
030513
040716
050518
060427
hæð yfir sjó / m a.s.l.
lengd / length (km)
1
15
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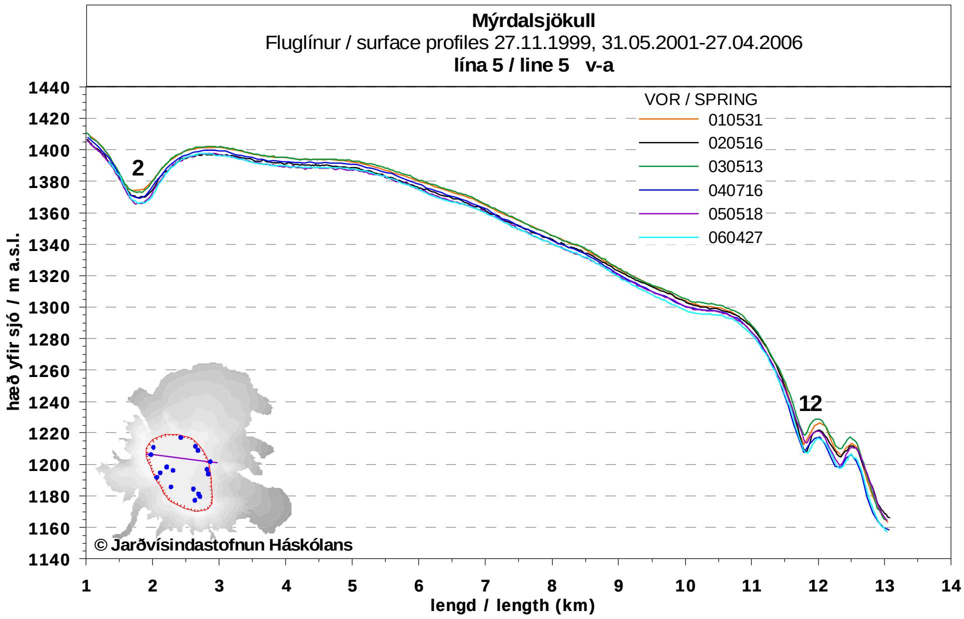
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Fluglínur / surface profiles 27.11.1999, 31.05.2001-27.04.2006
lína 5 / line 5 v-a
VOR / SPRING
010531
020516
030513
040716
050518
060427
hæð yfir sjó / m a.s.l.
lengd / length (km)
2
12
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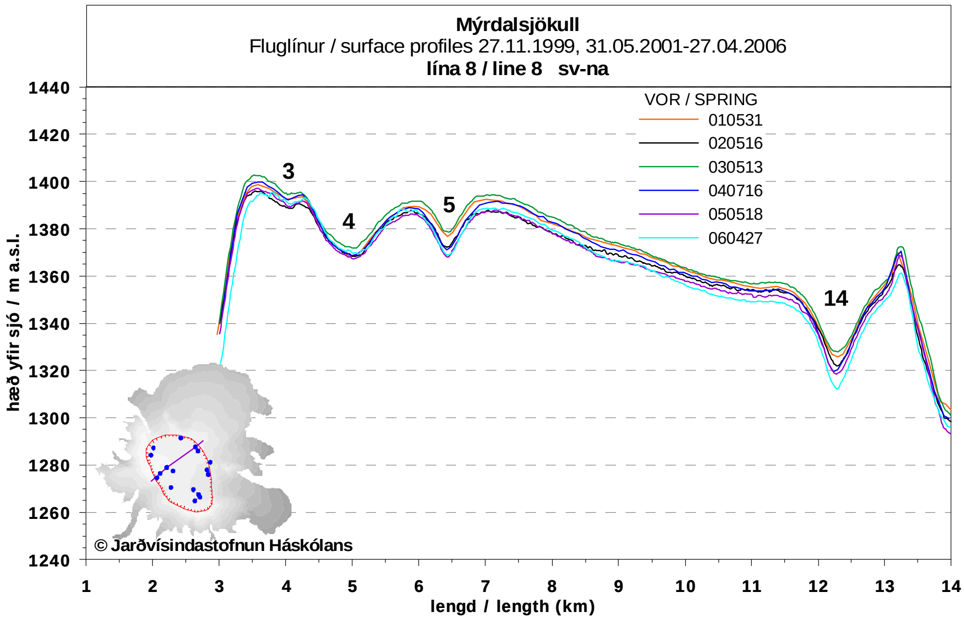
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Fluglínur / surface profiles 27.11.1999, 31.05.2001-27.04.2006
lína 8 / line 8 sv-na
VOR / SPRING
010531
020516
030513
040716
050518
060427
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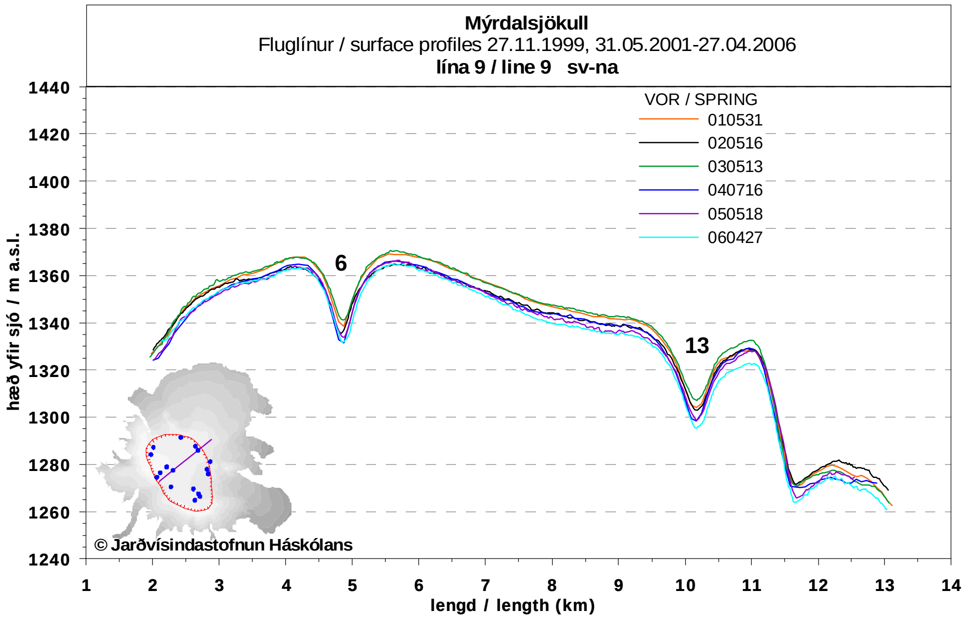
4
5
14
hæð yfir sjó / m a.s.l.
lengd / length (km)
© Jarðvísindastofnun Háskólans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lína 9 / line 9 sv-na
VOR / SPRING
010531
020516
030513
040716
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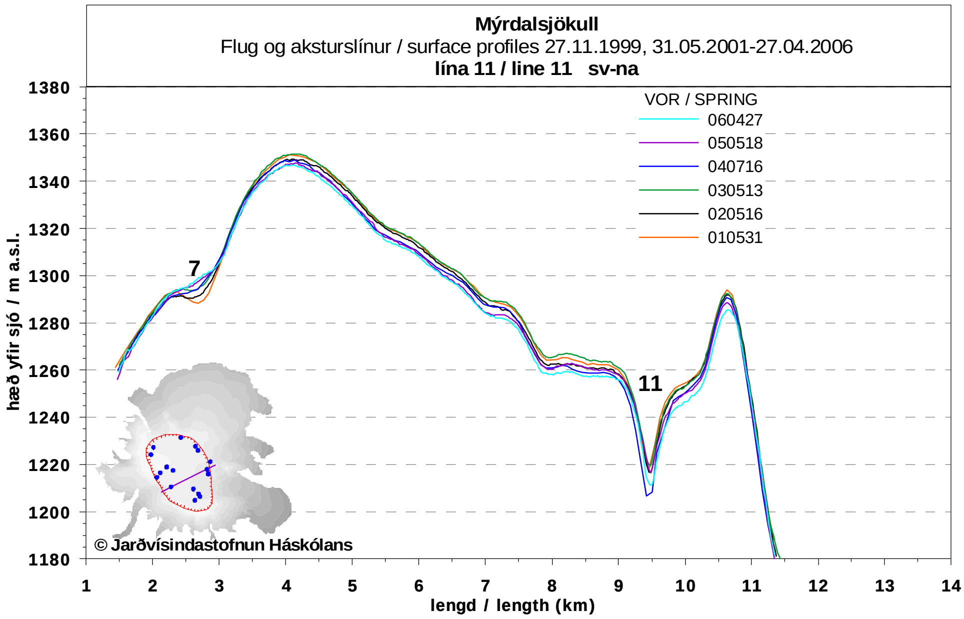
13
hæð yfir sjó / m a.s.l.
lengd / length (km)
© Jarðvísindastofnun Háskólans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lína 11 / line 11 sv-na
VOR / SPRING
060427
050518
040716
030513
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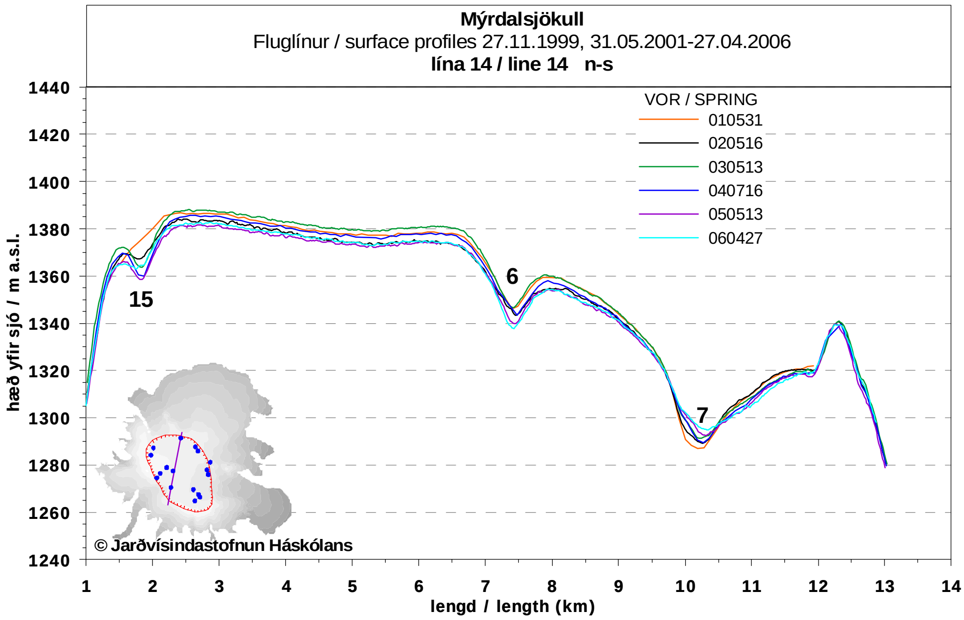
010531
7
11
hæð yfir sjó / m a.s.l.
lengd / length (km)
© Jarðvísindastofnun Háskólans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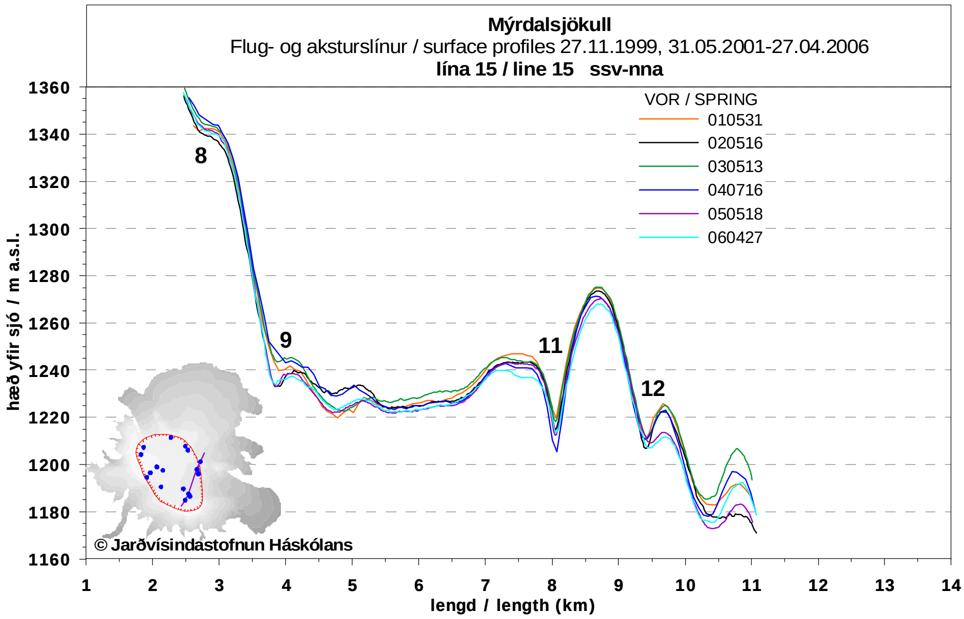
Fluglínur / surface profiles 27.11.1999, 31.05.2001-27.04.2006
lína 14 / line 14 n-s
VOR / SPRING
010531
020516
030513
040716
050513
060427
hæð yfir sjó / m a.s.l.
lengd / length (km)
15
6
7
© Jarðvísindastofnun Háskólans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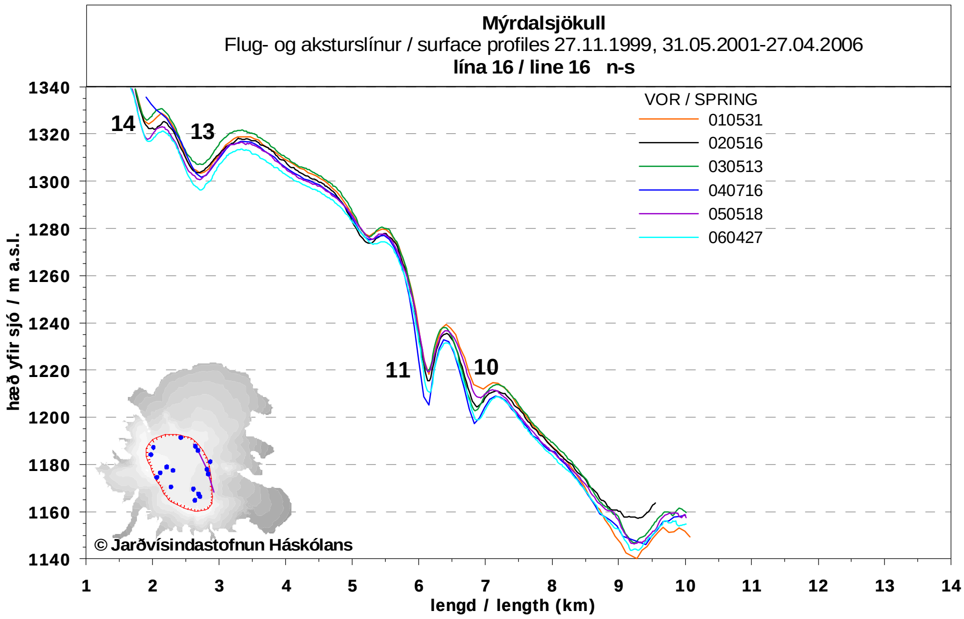
Flug- og aksturslínur / surface profiles 27.11.1999, 31.05.2001-27.04.2006
lína 15 / line 15 ssv-nna
VOR / SPRING
010531
020516
030513
040716
050518
060427
hæð yfir sjó / m a.s.l.
lengd / length (km)
8
9
11
12
© Jarðvísindastofnun Háskólans


Mýrdalsjökull
Flug- og aksturslínur / surface profiles 27.11.1999, 31.05.2001-27.04.2006
lína 16 / line 16 n-s
VOR / SPRING
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020516
030513
040716
050518
060427
hæð yfir sjó / m a.s.l.
lengd / length (km)
14
13
11
10
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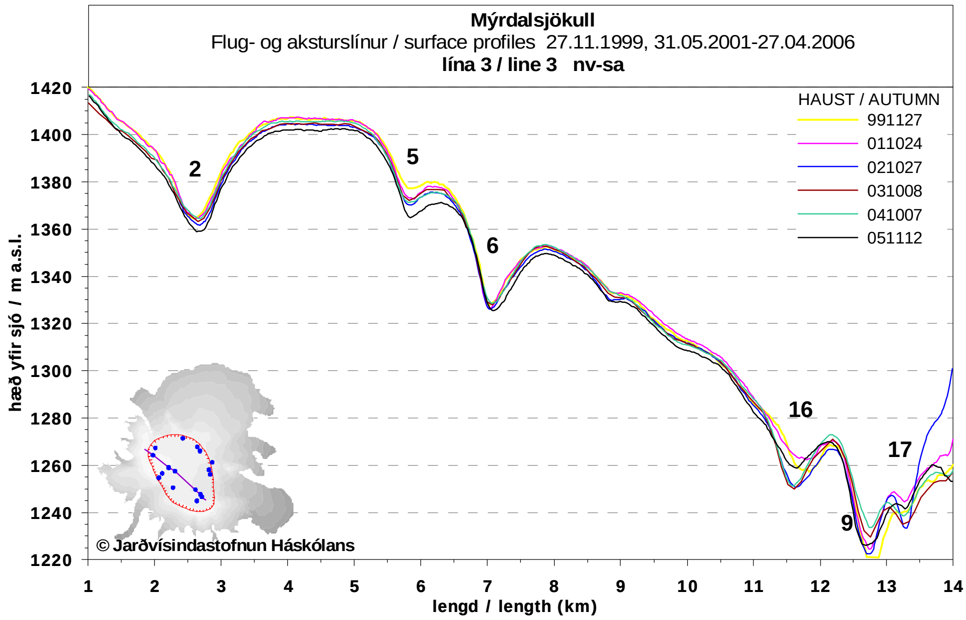
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lína 3 / line 3 nv-sa
HAUST / AUTUMN
991127
011024
021027
031008
041007
051112
hæð yfir sjó / m a.s.l.
lengd / length (km)
2
5
6
16
17
9
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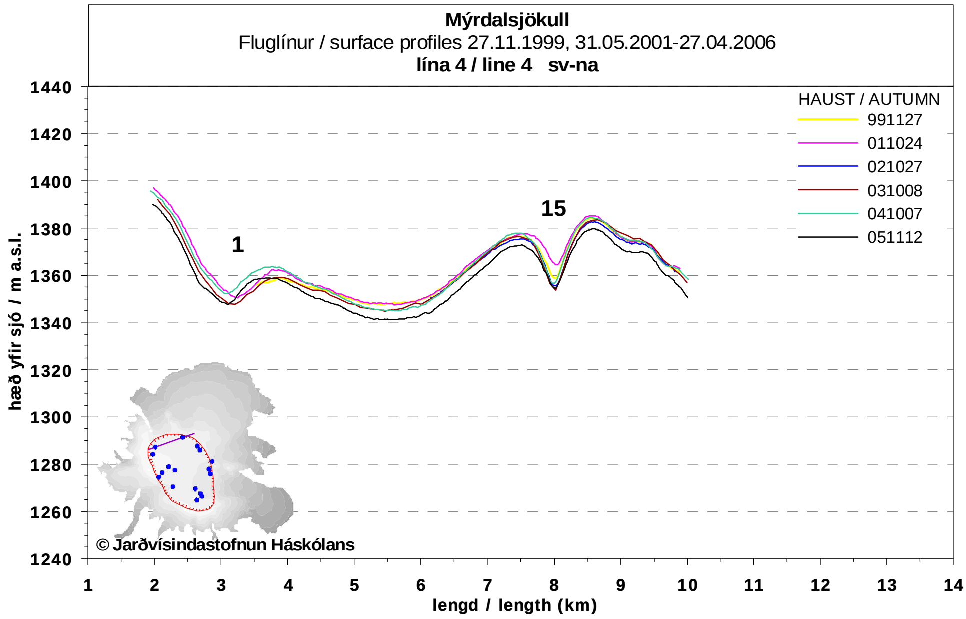
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lína 4 / line 4 sv-na
HAUST / AUTUMN
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011024
021027
031008
041007
051112
hæð yfir sjó / m a.s.l.
lengd / length (km)
1
15
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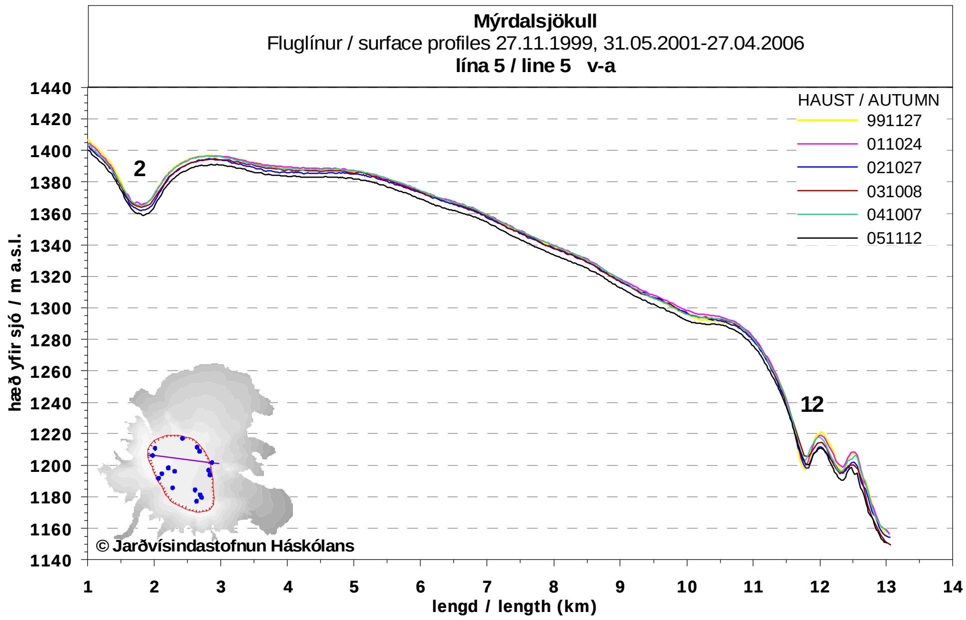
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lína 5 / line 5 v-a
HAUST / AUTUMN
991127
011024
021027
031008
041007
051112
hæð yfir sjó / m a.s.l.
lengd / length (km)
2
12
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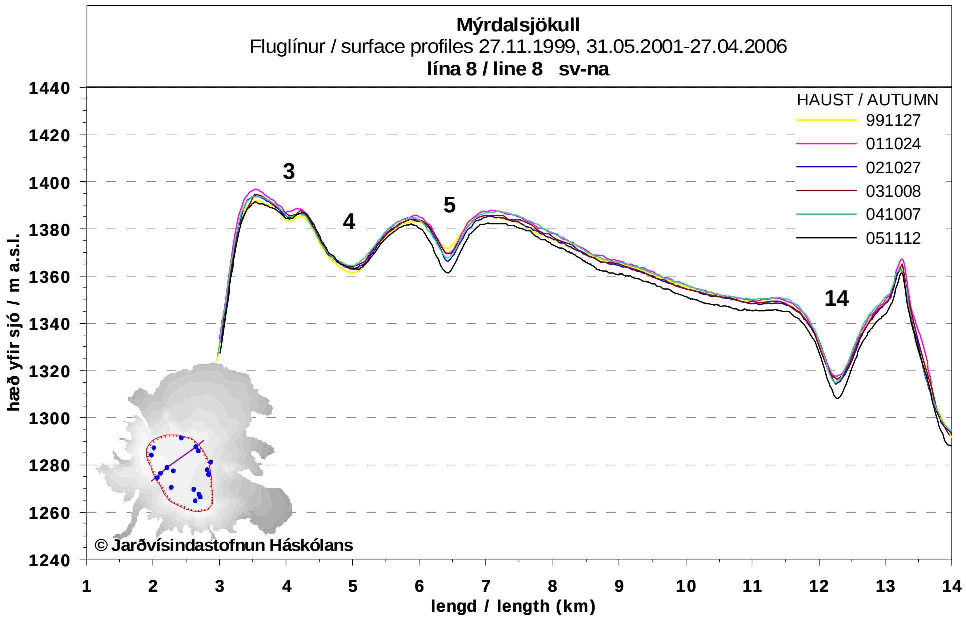
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lína 8 / line 8 sv-na
HAUST / AUTUMN
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011024
021027
031008
041007
051112
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4
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14
hæð yfir sjó / m a.s.l.
lengd / length (km)
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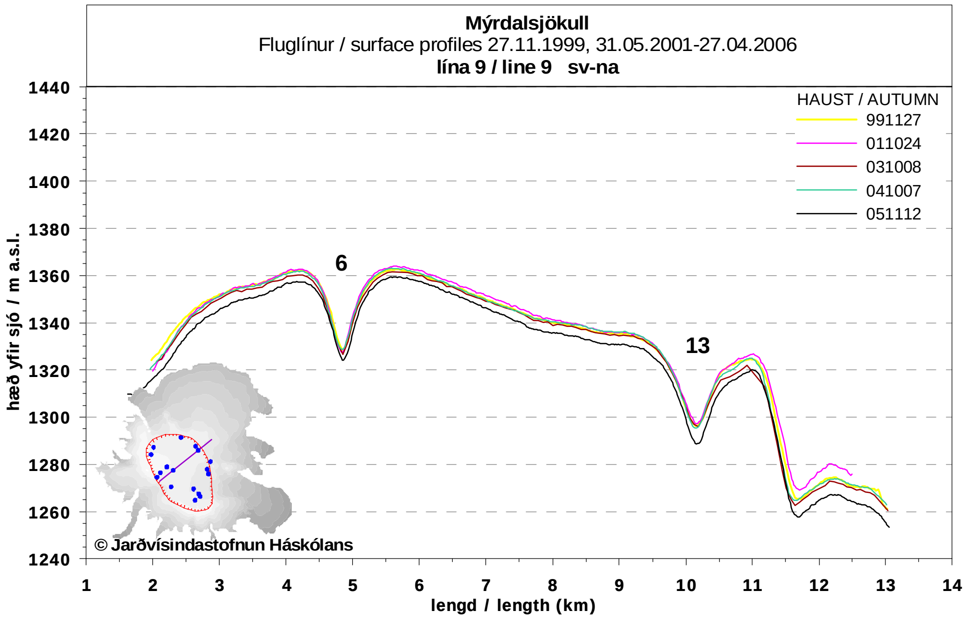
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HAUST / AUTUMN
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011024
031008
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hæð yfir sjó / m a.s.l.
lengd / length (km)
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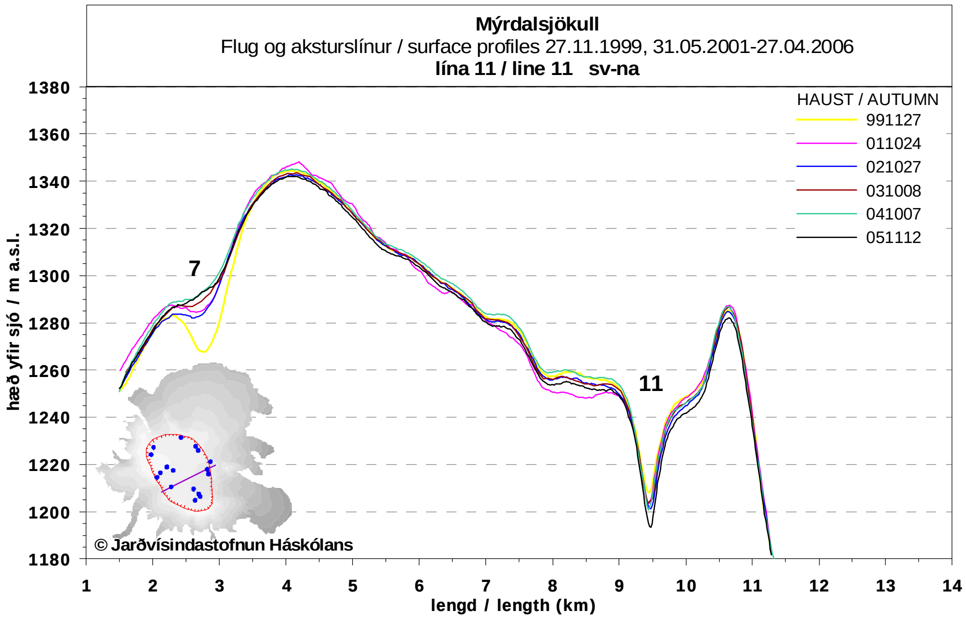
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hæð yfir sjó / m a.s.l.
lengd / length (km)
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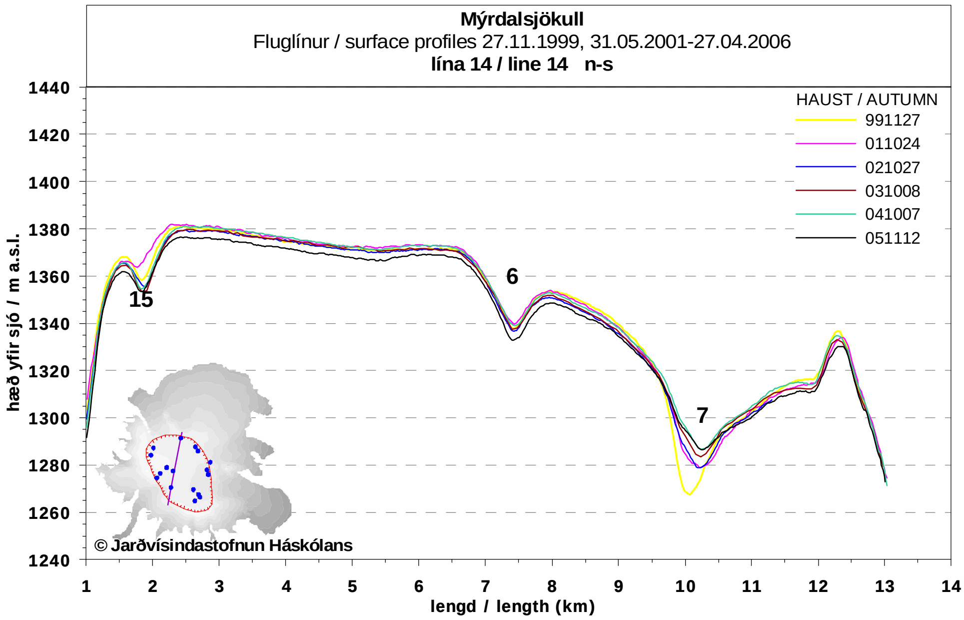
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Fluglínur / surface profiles 27.11.1999, 31.05.2001-27.04.2006
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HAUST / AUTUMN
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hæð yfir sjó / m a.s.l.
lengd / length (km)
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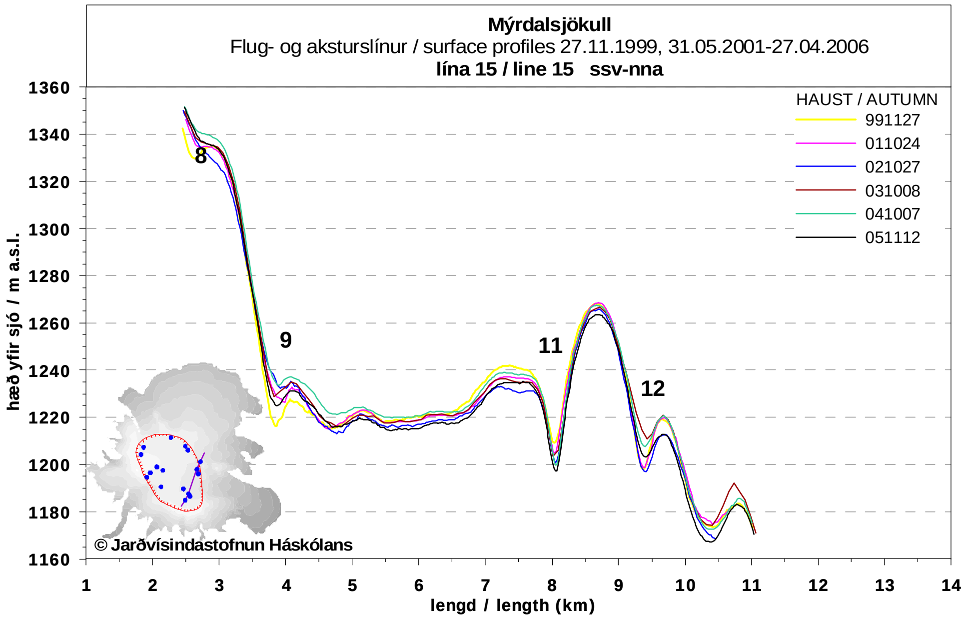
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lengd / length (km)
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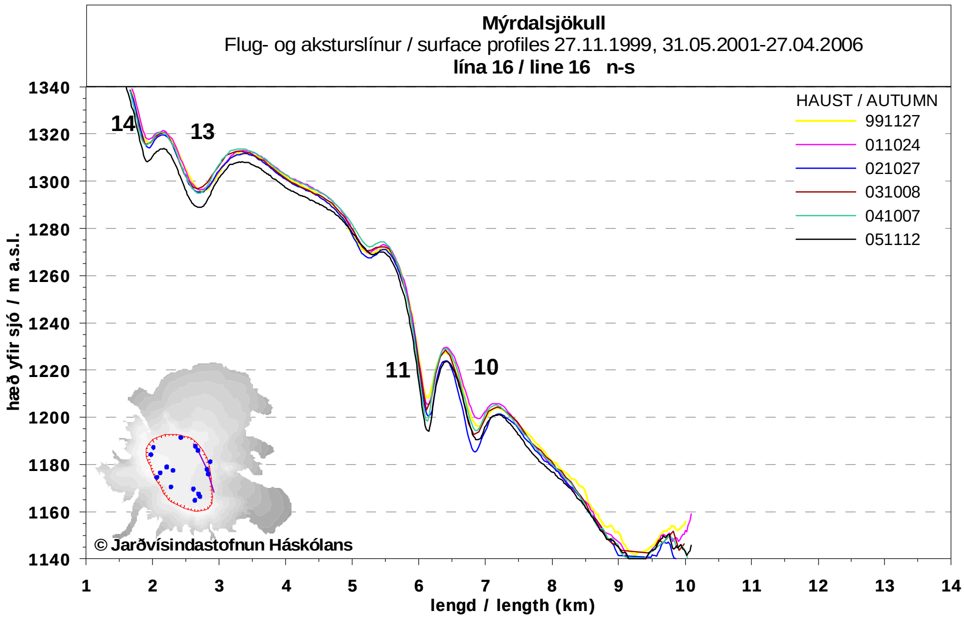
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hæð yfir sjó / m a.s.l.
lengd / length (km)
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