LV-2006/104

Modelling ice formation in Lower Þjórsá

Using data from the MM5 meteorological model for the winters 2000–2006

Landsvirkjun

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Title:	Modelling ice formation in Lower Þjórsá. Using data from the MM5 meteorological model for the winters 2000–2006
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Abstract: Large amounts of frazil ice in Þjórsá accumulates and forms the Urriðafoss ice jam, the largest freeze-up jam in Iceland. In this report, results from runs of the ice production model by Gröndal (2003) are presented and discussed for the years 2000–2006. The intention of the study at hand is to improve the ice production model by using output from the MM5 meteorological model, which has been run on a 8 x 8 km grid with 6 hour temporal resolution.

Keywords: Þjórsá, ice formation, MM5, modelling

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Landsvirkjun's project manager's signature

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1 INTRODUCTION

Þjórsá downstream from Búrfell power plant (Fig. 1) has a large hydro power potential, and currently, plans are being drafted on how hydro power production can be developed in this lower reach of Þjórsá. A number of different potential problems have been identified in this context, one of which is the formation of frazil ice in the open water areas along the length of Þjórsá downstream of Búrfell. Large amounts of frazil ice, which amount to many tonnes/s, form under certain meteorological conditions. The frazil ice is carried with the flow from upstream to the low sloping reach downstream of Urriðafoss waterfall (Fig. 1) where it accumulates and builds up to form the Urriðafoss ice jam, the largest freeze-up jam in Iceland.

The construction of hydro power plants in Lower Þjórsá will change the natural ice conditions in the river, but even so, parts of the river which remain open during winter can still produce large amounts of frazil ice which can cause serious difficulties in the operation of the planned hydro power plants. Unless measures are taken to reduce frazil ice production, frazil ice might accumulate and form jams in the intake reservoirs which would cause flooding of adjacent areas and disturbances in water flow to the power stations.

In this report, results from runs of the ice production model described by Gröndal (2003) are presented and discussed. Previously, the ice production model has been run with data from the weather station at Hæll, with results which compare quite well with observations of the size of the Urriðafoss ice jam (Gröndal & Helgason, 2003). The intention of the study at hand is to improve the ice production model by using output from the MM5 meteorological model, which has been run on an 8 x 8 km grid with 6 hour temporal resolution (MM5, 2006; Rögnvaldsson, 2006).

A short explanation of a few terms used in the report:

- *border ice*
  a continuous ice cover which has formed along the banks of a river by in situ freezing or by accumulation and subsequent freezing of ice floes in a single layer
- *frazil ice*
  fine particles of ice suspended in water; frazil ice forms in supercooled turbulent waters
- *ice cover*
  ice on the surface of a body of water, does not move relative to the water
- *ice floe*
  ice on the surface of a body of water, does move with the water flow
- *ice jam*
  a stationary accumulation of frazil ice or fragmented ice, which blocks the channel it has formed in
- *open water surface*
  liquid water surface which may be partly covered in moving ice floes or slush
- *slush ice*

a mix of snow and ice particles, including frazil ice, broken border ice and surfaced anchor ice, moving with the water flow.

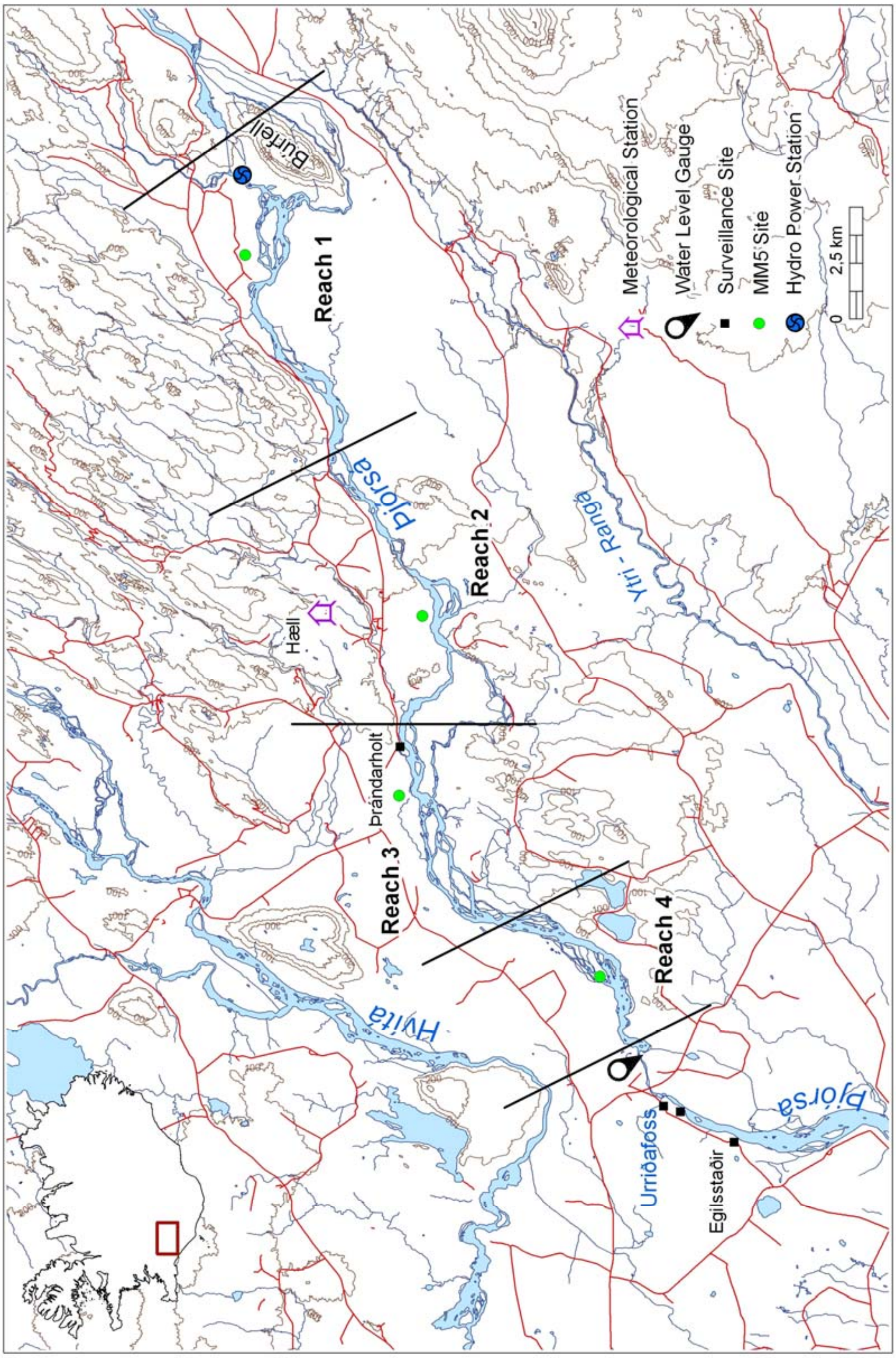

Figure 1: *Þjórsá downstream of the Búrfell power plant. Locations of surveillance cameras, the Hæll weather station, MM5 grid points, and the water level gauge at Urriðafoss are shown. Subreaches used in the ice calculation model are also shown. (Map: Bogi Brynjar Björnsson).*

2 INVESTIGATION OF ICE CONDITIONS 2000–2006

Rist (1962) compiled a comprehensive description of the ice conditions in Lower Þjórsá, which provides the basis for the current understanding of the ice conditions in the river reach. In order to add to this understanding, Landsvirkjun initiated a systematic ice observation programme in Lower Þjórsá in 2000. Three automatic water level gauges were installed downstream of Urriðafoss, with the intention to monitor the build up of the Urriðafoss ice jam (Helgason, 2002). In addition, automatic surveillance cameras have been in operation since the winter 2002/2003, and numerous surveillance trips, both from ground and air, have provided valuable information which is used to validate the results of the numerical models which have been constructed.

2.1 Measurement of water levels at Urriðafoss

The water level gauges at Urriðafoss (fig. 1) record water levels on an hourly basis. The data gives information about the growth rate and size of the jam, which in turn is utilised when assessing the amount of frazil produced during ice production events. It is possible to construct a relationship which can predict the total volume of the jam from readings on the water gauges. This requires maps of the bathymetry of the river channel and topography of the surrounding areas. But the jam itself is not a static accumulation of solid ice floating on the water. Rather, it is a dynamic mass which is altering shape as frazil ice is accumulating, eroding and consolidating. The ice, water and air composition of the jam is therefore changing throughout the lifespan of the jam. The readings on the water gauges at Urriðafoss thus indicate gross jam volumes, including floating solid ice, backwater, water level rise because of increased friction, and water and air trapped in the pores of the jam. Estimates of the actual volume of solid ice in the jam are best done on the basis of information about the actual thickness of the ice accumulations and the porosity of the ice jam. Direct measurements of these parameters in the ice jam are too dangerous to be applicable, which means that the solid ice volume in the jam has been estimated from surface elevation of the jam and by solving a lengthwise force balance through the jam (Gröndal, 2003).

2.2 Photographic surveillance

Automatic surveillance cameras have been in operation since 2003 at four different locations along Þjórsá (Fig. 1). Photographs from the cameras show how the ice conditions in the river change on an hourly basis during daylight hours. The photographs are used to interpret water level changes at Urriðafoss, and they show floating ice and border ice growths in and along the river, which is used when assessing the accuracy of the ice production model. Remote operation of the surveillance cameras, e.g. by phone lines, has not yet been tried. The capacity of the phone lines currently available do not make on-line connection to the cameras feasible, however, experience is being gained through the use of these cameras which will become valuable in the future in the design of monitoring and early warning systems for ice formation in the river.

Photographic material from Urriðafoss shows that the jam can advance up river many hundred meters per day, and once formed, the jam is a very dynamic mass, which is constantly changing shape and moving both vertically and horizontally. Vertical movements of the jam are attributed to changes in water or hydrostatic pressure levels in the jam, which are caused by fluctuations in discharge and changes in flow friction. In addition, the surface of the jam rises because of accumulation of ice from below, and through lengthwise consolidation. Horizontal movement in the lengthwise direction of the jam is caused by shoving, i.e. lengthwise consolidation of the ice jam. Observed rates at which the jam shoves can amount to several meters per hour near water gauge U02. Apparently, first after the formation of the jam, shoving occurs on a large scale everywhere in the jam. This can be expected, as the initial composition of the jam is relatively loosely packed slush ice with little resistance to deformation. Later, when the overall mechanical strength of the jam has increased, because of consolidation and freezing of the liquid water in the jam, shoving appears to happen at more confined locations, hence the fracture ridges which are quite prominent in a mature jam.

Surveillance photographs from Þrándarholt show that border ice occupies a large proportion of the channel width during periods of cold weather. The border ice is formed by freezing of water along the river banks, but the growth rate of border ice is very much affected by accumulation of frazil and slush ice in the bank areas. At Þrándarholt, border ice can occupy in the order of one-third to half of the total channel width, and, although the water surface may become completely covered in slush and frazil ice, a static ice cover across the river channel does not form. Flow velocities in the centre part of the river are too high for that to happen.

Surveillance trips have been carried out on numerous occasions with the aim to observe the ice conditions along Þjórsá (e.g. Gröndal and Helgason, 2003; Helgason and Gröndal, 2006). Of particular importance are airborne surveillance trips, through which the size of the open water area in Þjórsá can be determined. Frazil and slush ice can only form in open water areas, and open water area is therefore a key parameter in modelling ice production along the river. Photographic material, both from ground and from the air, has been used to construct maps of frazil ice producing areas, and to measure their size. Observations indicate that the size of open water area changes quite rapidly during the ice events. Low flow velocity channels close completely and border ice attaches to the shore which reduces the open water surface of the river by many km^2. Observations indicate that during mature state of ice development, open areas, i.e. areas which are not covered by static border ice growths, measure about 11–15 km^2.

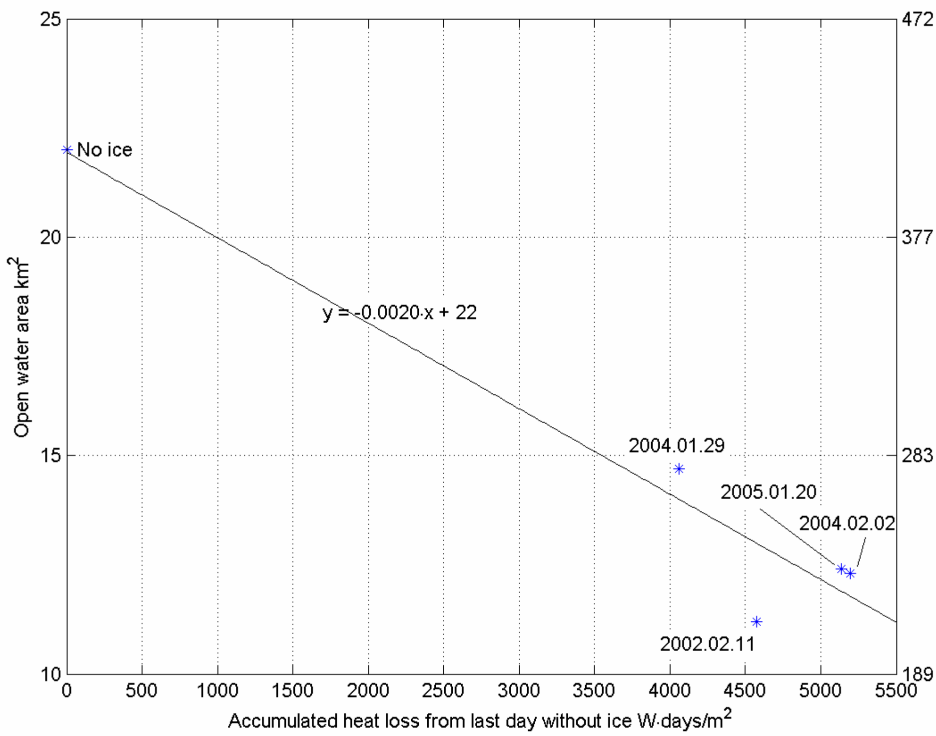

Figure 2: *Open water area and accumulated heat loss. Data from Helgason and Gröndal (2006) and Helgason (2002).*

At any time during a period with ice in the river, the amount and state of the border ice depends on how rapidly border ice has been attaching to the shore due to freezing and how rapidly the same border ice has been deteriorating and breaking due to thawing and the action of mechanical forces. These processes are related to the hydraulics of the river channel in addition to the present as well as recent climatic conditions. Figure 1 shows open water area in Lower Þjórsá plotted against accumulated heat loss from the most recent day without any border ice in the river to the day of measurement. The heat loss time series corresponding to each occasion can be viewed in Appendix 3. The relationship presented is a rough estimate of the correlation between open water area and accumulated heat loss during a cold period in mid winter, which should not be used to predict ice break-up in the river.

2.3 Calculation of ice discharge

The heat loss and ice production model which is used in the analysis has been described previously by Gröndal (2003). In previous configurations, the model has used meteorological data from the nearby Hæll weather station, and the model has been found to perform quite well in predicting total amount of ice produced in the river. However, Hæll represents only one point in the river basin, and time resolution of the data from Hæll is 24 hours. Moreover, the data from Hæll do not include records of vapour pressure, and wind speed is estimated rather than measured directly. Therefore it was decided to try to improve the ice production calculations by using data from model runs from the PSU/NCAR MM5 model (Penn State University / National Centre for Atmospheric Research, Mesoscale Model (MM5, 2006)), applied by Rögnvaldson (2006).

Output from the MM5 model consists of time series of air temperature, wind speed, vapour pressure, incoming short wave (solar) radiation, incoming long wave radiation and other variables (MM5, 2006). On the basis of above mentioned variables, heat loss from an open water surface at 0°C is calculated. Heat flux from the water surface due to convection and evaporation is calculated according to Freysteinsson & Björnsson (1971):

Convection:

$$\Phi_H = [3{,}89 + 0{,}17 \cdot (T_w - T_a) + 1{,}88 \cdot W] \cdot (T_w - T_a) \qquad [\mathrm{Wm^{-2}}] \qquad (1)$$

Evaporation

$$\Phi_E = [6{,}07 + 0{,}27 \cdot (T_w - T_a) + 2{,}93 \cdot W] \cdot (e_s - e_a) \qquad [\mathrm{Wm^{-2}}] \qquad (2)$$

In the above expressions, $T_w \approx 0$°C represents the surface temperature of the water, e_s saturation vapour pressure [hPa] corresponding to T_w, T_a represents air temperature [°C], e_a vapour pressure [hPa] and W represents wind speed [$\mathrm{ms^{-1}}$], all measured 2 m above ground.

Net outgoing long wave radiation is determined according to

$$\Phi_L = \varepsilon_w \cdot \sigma \cdot T_w^4 - \varepsilon_w \cdot \Phi_{L,atm} \qquad [\mathrm{Wm^{-2}}] \qquad (3)$$

In which the emittance of water $\varepsilon_W = 0{,}97$, the Stefan-Boltzmann coefficient $\sigma = 5{,}67 \cdot 10^{-8}$ $\mathrm{Wm^{-2}K^{-4}}$, $T_W \approx 273$ K is the surface temperature of the water, and $\Phi_{L,atm}$ represents incoming long wave radiation from the atmosphere, calculated by the MM5 model.

Net incoming solar radiation is determined according to

$$\Phi_S = (1 - \alpha) \cdot \Phi_{S,tot} \qquad [\mathrm{Wm^{-2}}] \qquad (4)$$

In the expression, α represents the albedo of the water ($\alpha \approx 0{,}1 - 0{,}3$) and $\Phi_{S,tot}$ is total incoming solar radiation according to the MM5 model.

Total heat loss from an ice producing water surface is the sum of the above terms, i.e.

$$S = \Phi_H + \Phi_E + \Phi_L - \Phi_S \qquad [\mathrm{Wm^{-2}}] \qquad (5)$$

For further explanation of heat loss calculations, see Gröndal (2003) and Gröndal and Helgason (2003).

3 RIVER MODEL

Þjórsá downstream of Búrfell is divided into four approximately 10–15 km long reaches (Fig. 1). Data from one node of the MM5 model is used for each subsection of the river, the heat loss model thus calculates ice production in each sub section separately and output from one section are used as boundary conditions for the next downstream section.

Sub reach	Length km	Open water area km ^{2}	Average river width m	Average flow depth m
1	16	2.9	180	1.7
2	15	4.1	260	1.2
3	10	3.1	310	1.0
4	12	1.9	160	1.9

Table 1: *Parameters of the hydraulic model.*

Figures 3, 4 and 5 show a comparison between calculated ice production according to MM5 and Hæll weather data. As can be seen, there is good agreement between the results from these two data sets. However, the MM5 model run predicts less ice at Urriðafoss during periods with relatively mild weather, and accumulated ice mass at the end of winter is roughly 10–20% less when the MM5 data is used.

It was noted that the MM5 model run is usually in better agreement with photographic material from the surveillance camera at Þrándarholt and Urriðafoss 2 than the Hæll model runs, at least qualitatively. The Hæll run predicts ice on several occasions, when the MM5 correctly indicates that there is no ice in the river, see figures in Helgason and Gröndal, 2006 - Appendix (e.g. December 13, 23, 30, 31 2003; January 2–7, 10, 12 and 14 2004; November 13–14, 27–29 2004; December 2, 4–6, 9, 10, 12, 21, 29 2004; December 30 2005; January 3, 7–10 2006).

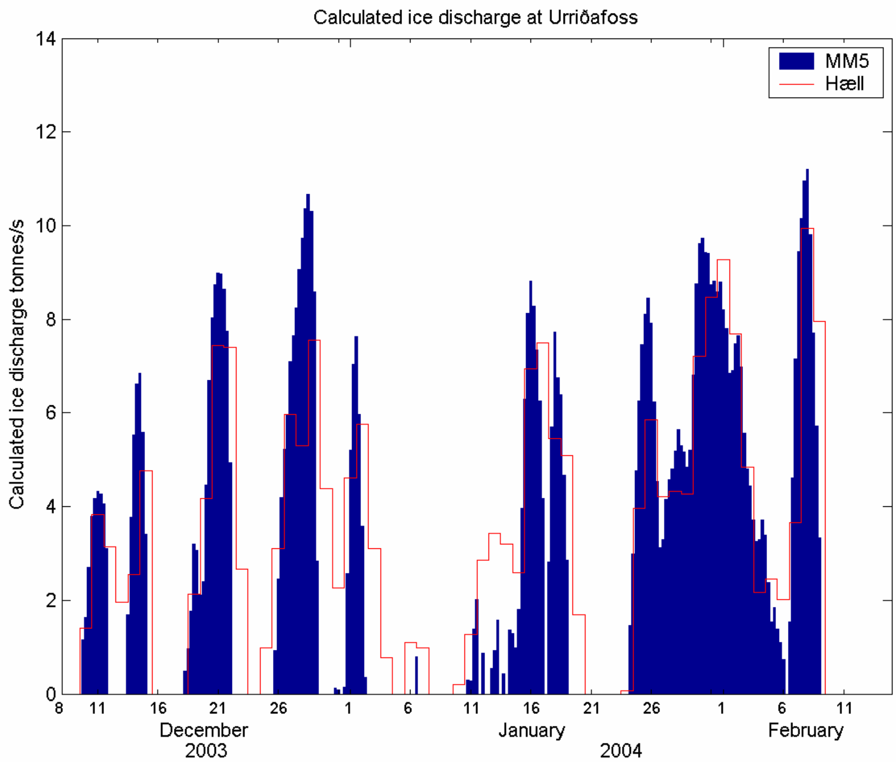

Figure 3: *Calculated ice discharge at Urriðafoss, December 2003 – February 2004.*

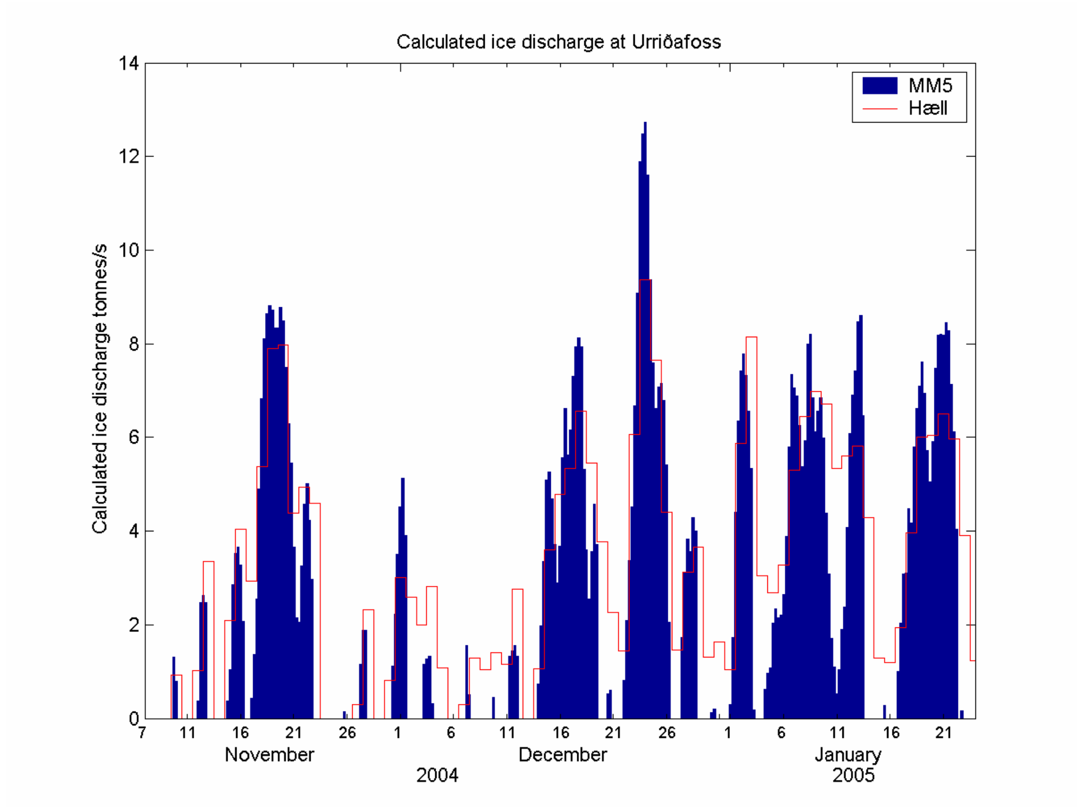

Figure 4: *Calculated ice discharge at Urriðafoss, November 2004 – January 2005.*

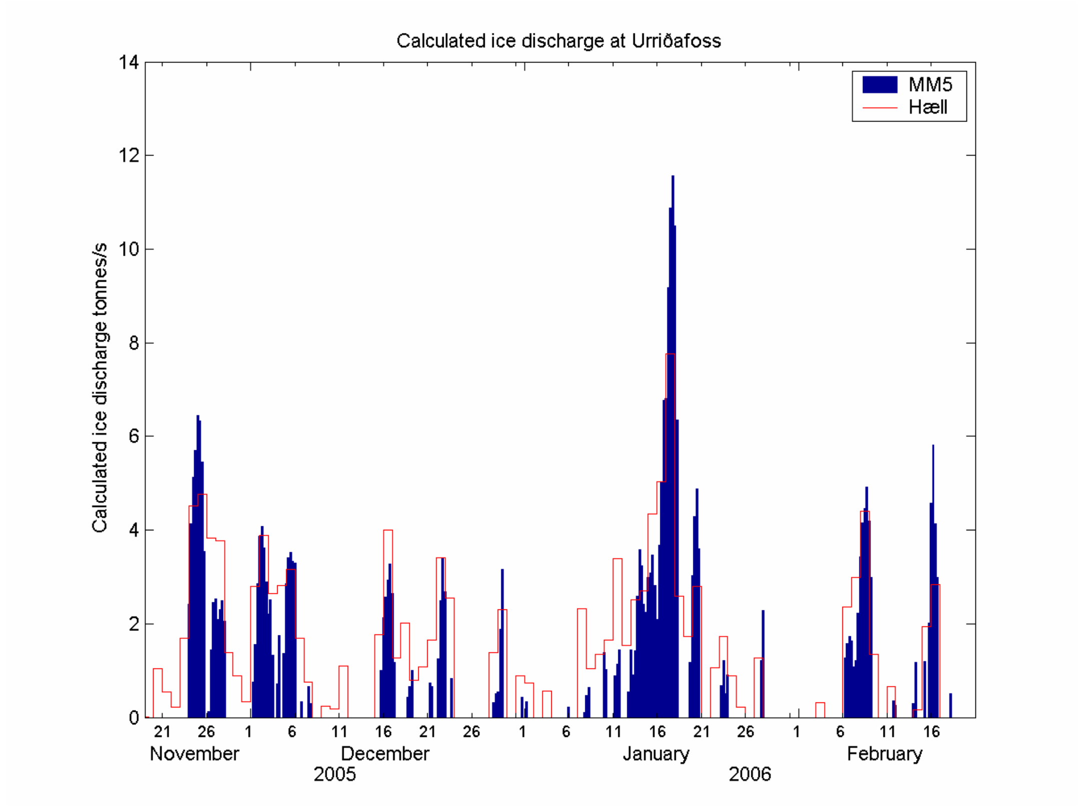

Figure 5: *Calculated ice discharge at Urriðafoss, November 2005 – February 2006.*

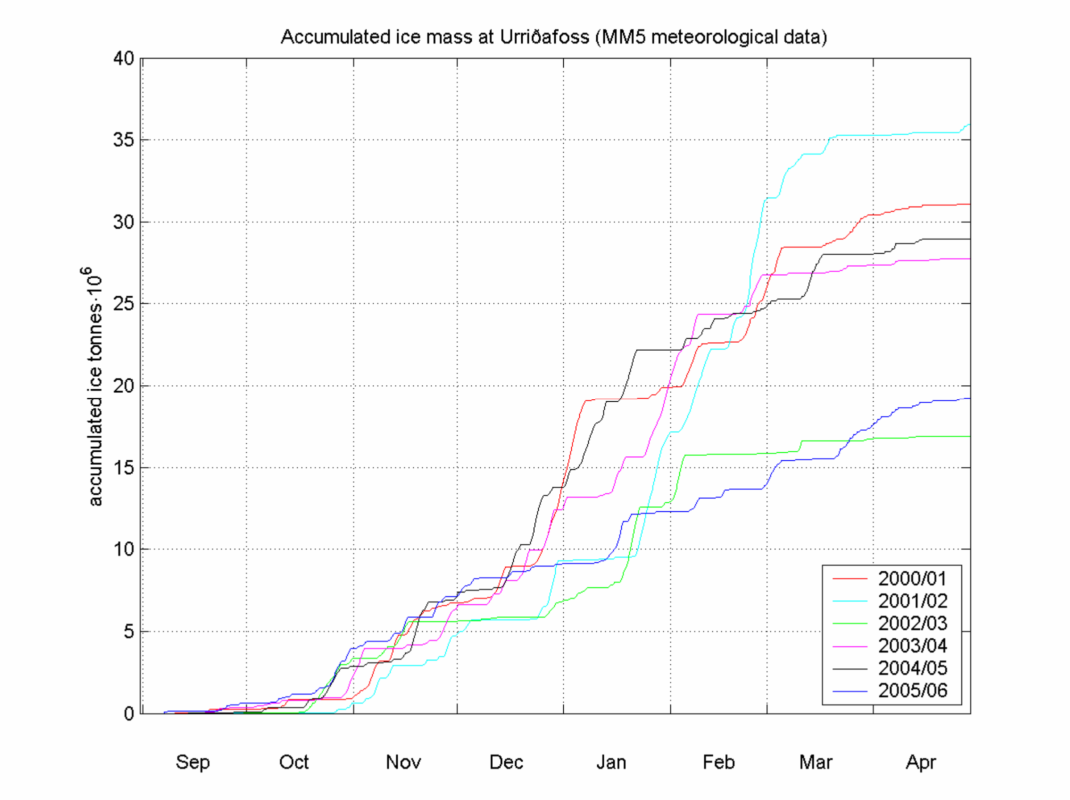

Figure 6: *Accumulated ice mass at Urriðafoss, according to calculations with meteorological data from MM5.*

Figure 6 shows accumulated ice mass at Urriðafoss according to the MM5 model run. As already mentioned, the MM5 data predict roughly 10–20% less total ice mass at Urriðafoss (Fig. 7). This discrepancy is to a large extent attributed to the Hæll model run predicting too much ice in the river during periods with relatively mild weather, when the photographic material shows that the river should have been more or less ice-free. The MM5 model run is more accurate in this respect. It is noted that during colder weather conditions, the MM5 and Hæll model runs agree quite well.

Figures 1–6 in Appendix 1 show the calculated ice discharge time series according to the MM5 model run.

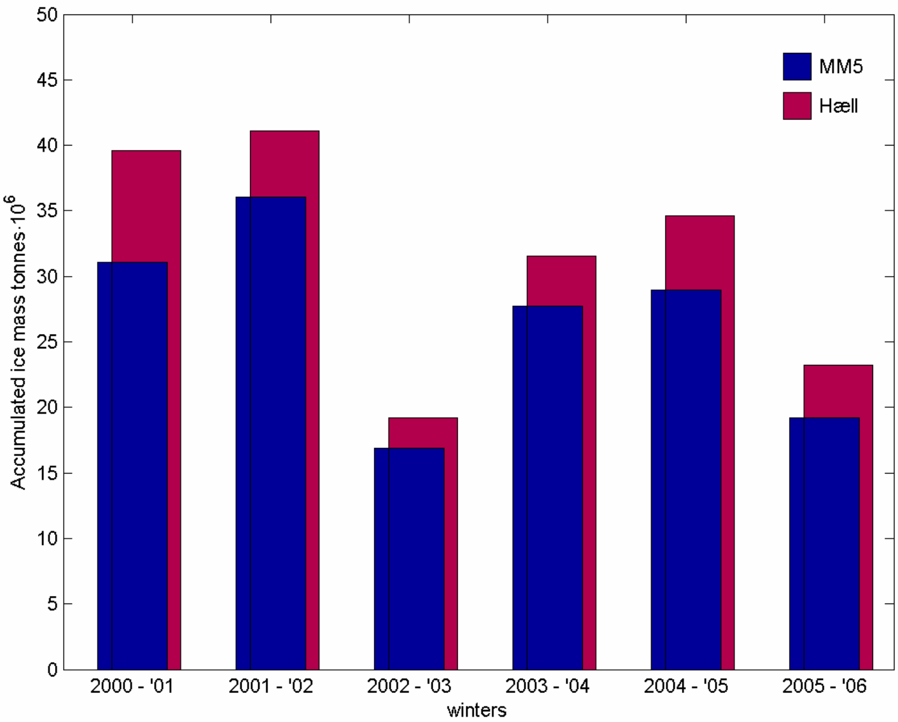

Figure 7: *Comparison of accumulated ice mass at Urriðafoss, according to MM5 and Hæll calculations.*

4 SUMMARY AND CONCLUSION

The use of meteorological data from the MM5 model is an improvement from using the Hæll dataset. The MM5 dataset leads to a reduction in the estimate of total amount of ice produced in Lower Þjórsá. According to MM5 about 20–30 million tonnes were produced annually in the period considered, compared to 20–40 million tonnes according to the Hæll run. The ice production model shows that during the winters 2000–2001 to 2005–2006 there were between 75–100 days with frazil ice in Þjórsá at Urriðafoss. Maximum ice discharge according to the model is about 19 tonnes/s in the period, but ice discharge rarely exceeds 10 tonnes/s, and is less than 5 tonnes/s in about 70% of the cases with ice.

Photographic evidence shows that the quality of the ice production model is improved when MM5 meteorological data is used as input in the model instead of data from Hæll weather station. The ice production model can be considered to be quite accurate in predicting ice formation in Þjórsá both qualitatively and quantitatively. Weaknesses of the model are related to simplifications of the geometry of the ice producing areas in the model. Further improvements of the model should aim at improving predictions of the size of the open ice producing areas in the river. The MM5 data make it feasible to use an ice production/ice transport model coupled with a more sophisticated model of the hydraulics of Lower Þjórsá to this respect.

Testing of the accuracy of the ice production model can be done through comparing the accumulated amount of ice with the size of the actual ice jam at Urriðafoss. Indeed, pressure level changes recorded by the water gauges in the Urriðafoss gorge are related to the amount of frazil and slush ice that accumulates in the jam. However, the jam is a dynamic mass which ice – water composition and shape is changing, and pressure levels in the jam thus provide relatively rough estimates of the actual mass of ice in the jam.

Direct measurements of ice discharge have not been applied at this stage, but previously, ice discharge measurements have been carried out in Þjórsá in order to validate ice production calculations. Kristinsson (1970) constructed a device for measuring ice discharge, which was composed of a rod suspended into the flow from a float and operated from land. Measurements of ice discharge made with this device at Sandafell in Þjórsá were used to validate ice discharge calculations in the period February to April 1969 with good results (Freysteinsson, 1970). Direct measurements of ice discharge, if successful, are the best way to validate calculation of ice production, and measurements of ice discharge in Lower Þjórsá should be considered for this purpose.

It has been found that visual observation of ice conditions in the river by means of automatic surveillance cameras is a valuable tool for testing the accuracy of the ice production model. The drawback of the cameras is that they can not observe ice conditions at night, icing sometimes covers the lenses, and it is difficult to interpret the precise geometry of the objects seen on the photographs. Improvements could therefore be night vision sensors and photogrammetric surveying quality setup of the equipment.

The ice production model can be used to predict how ice conditions along Þjórsá will change in future, by using climate scenario meteorological data sets. However, it is recommended that this should be done in conjunction with open water surface area models.

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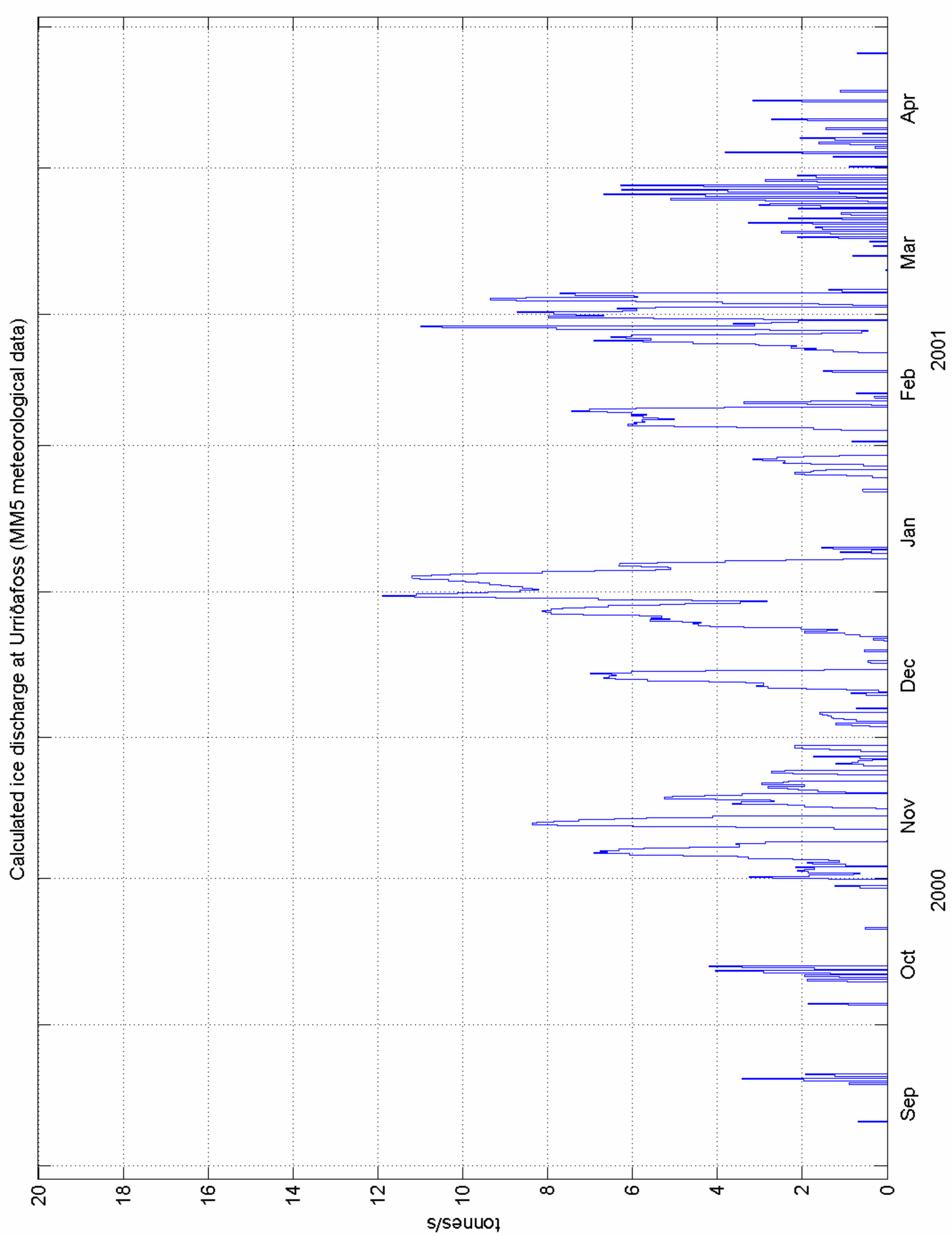
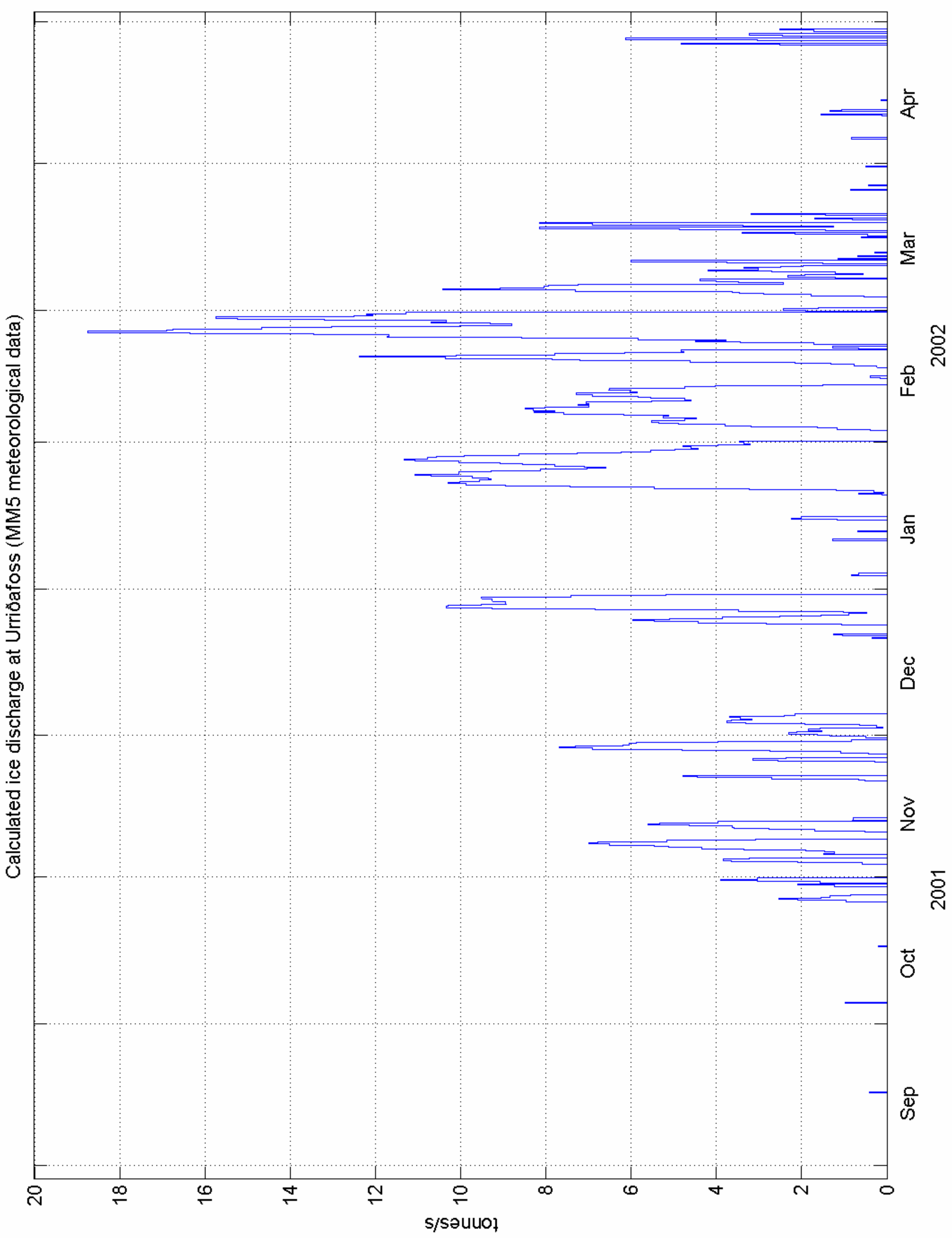
Appendix 1. Calculated ice discharge according to MM5 meteorological data.

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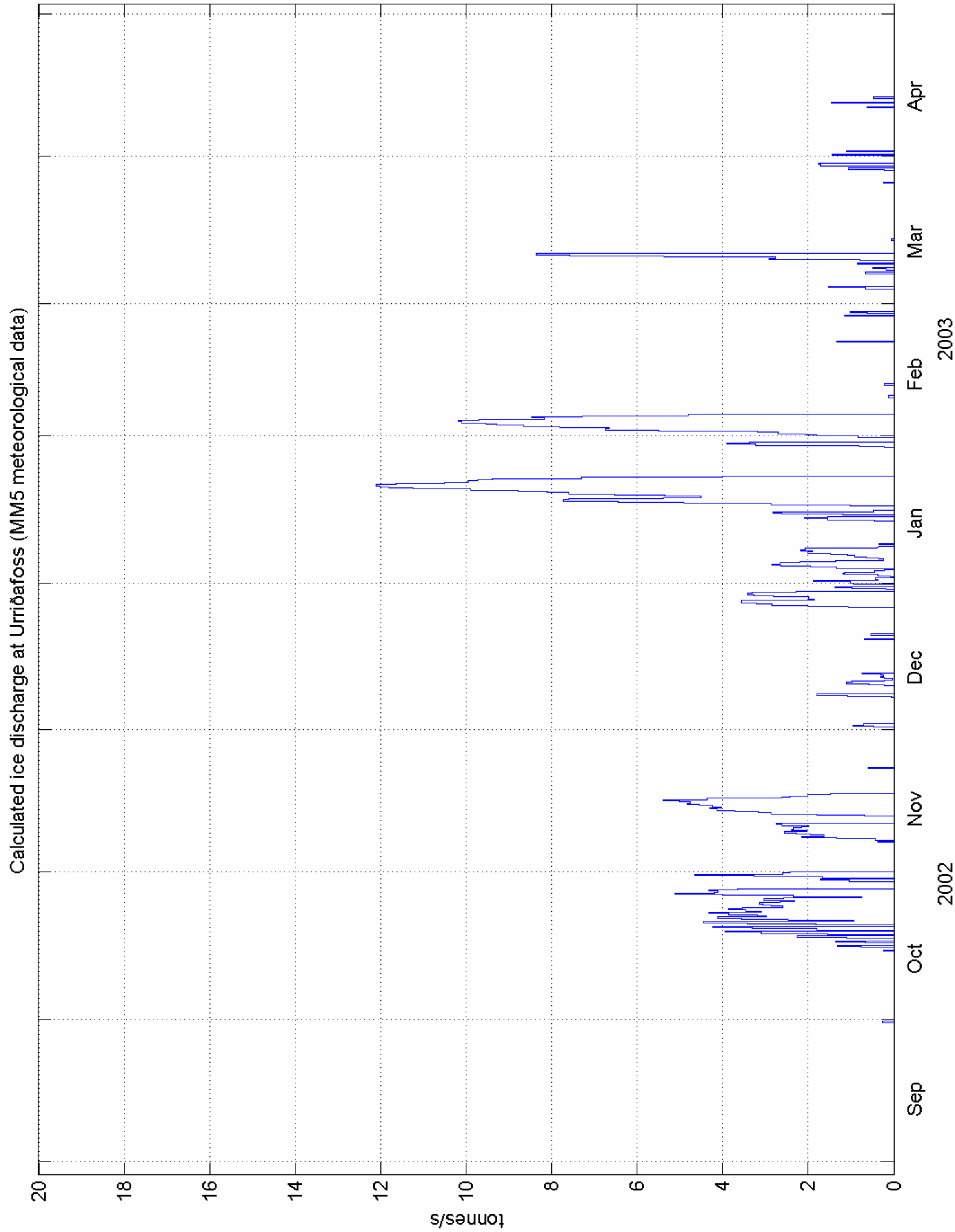
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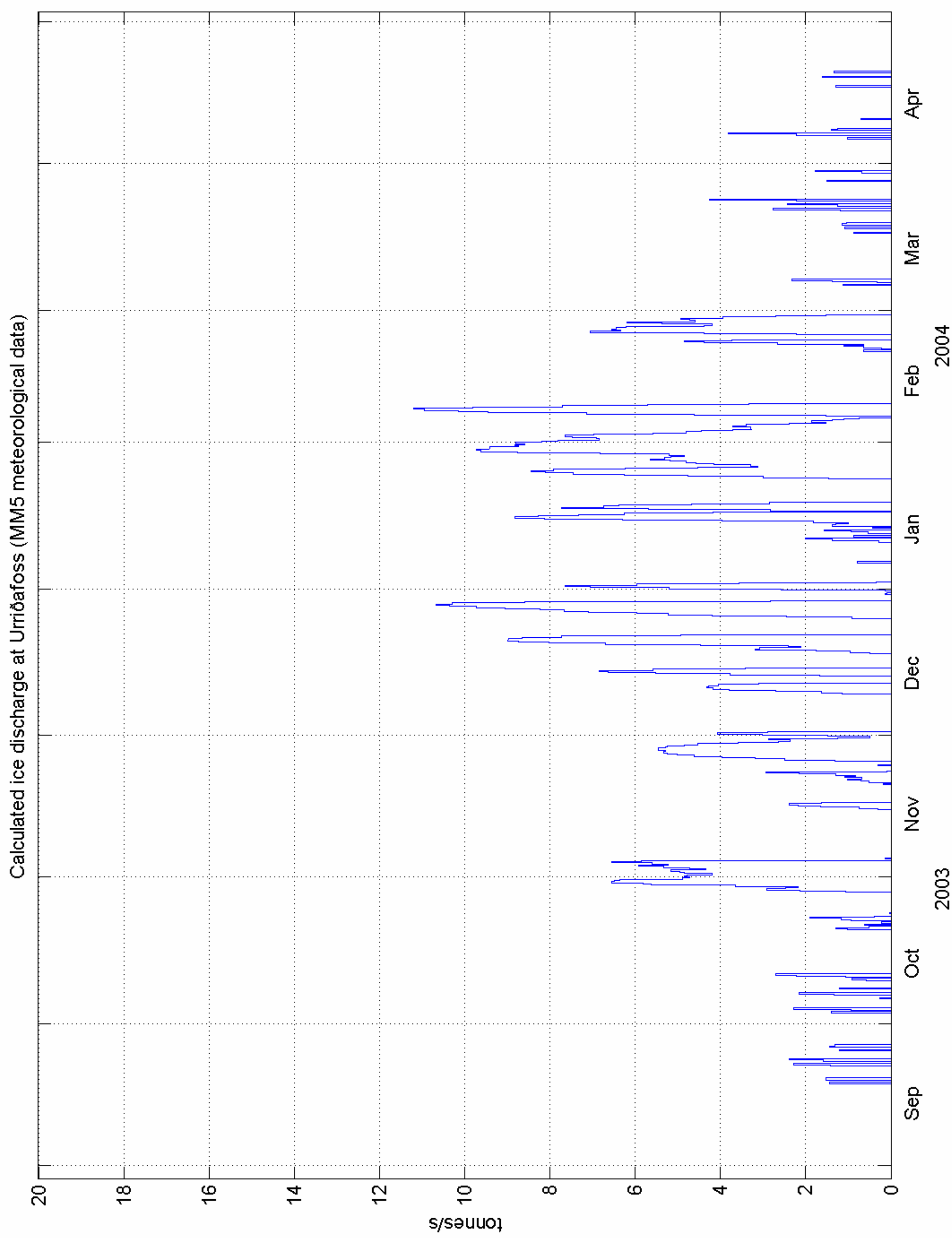

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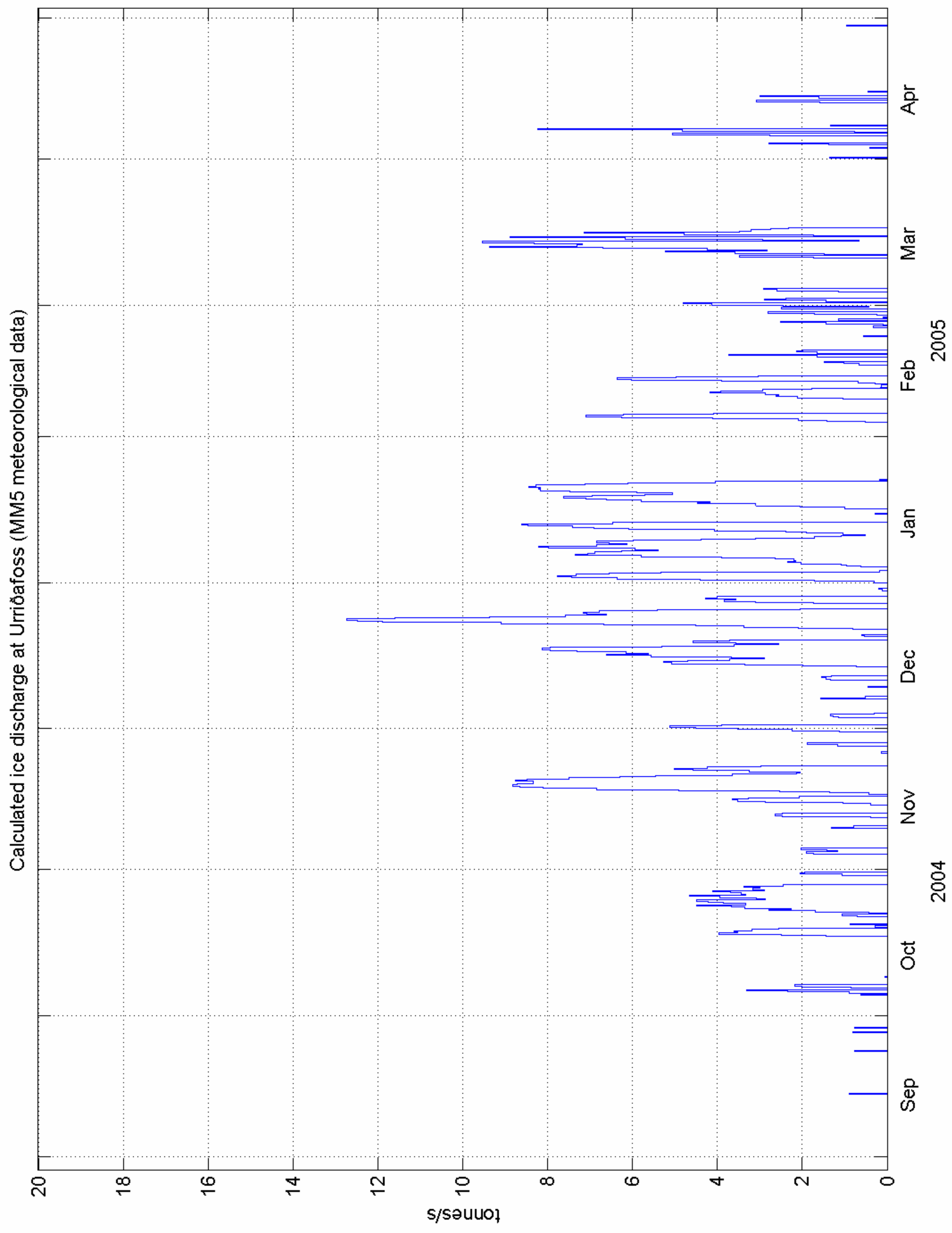
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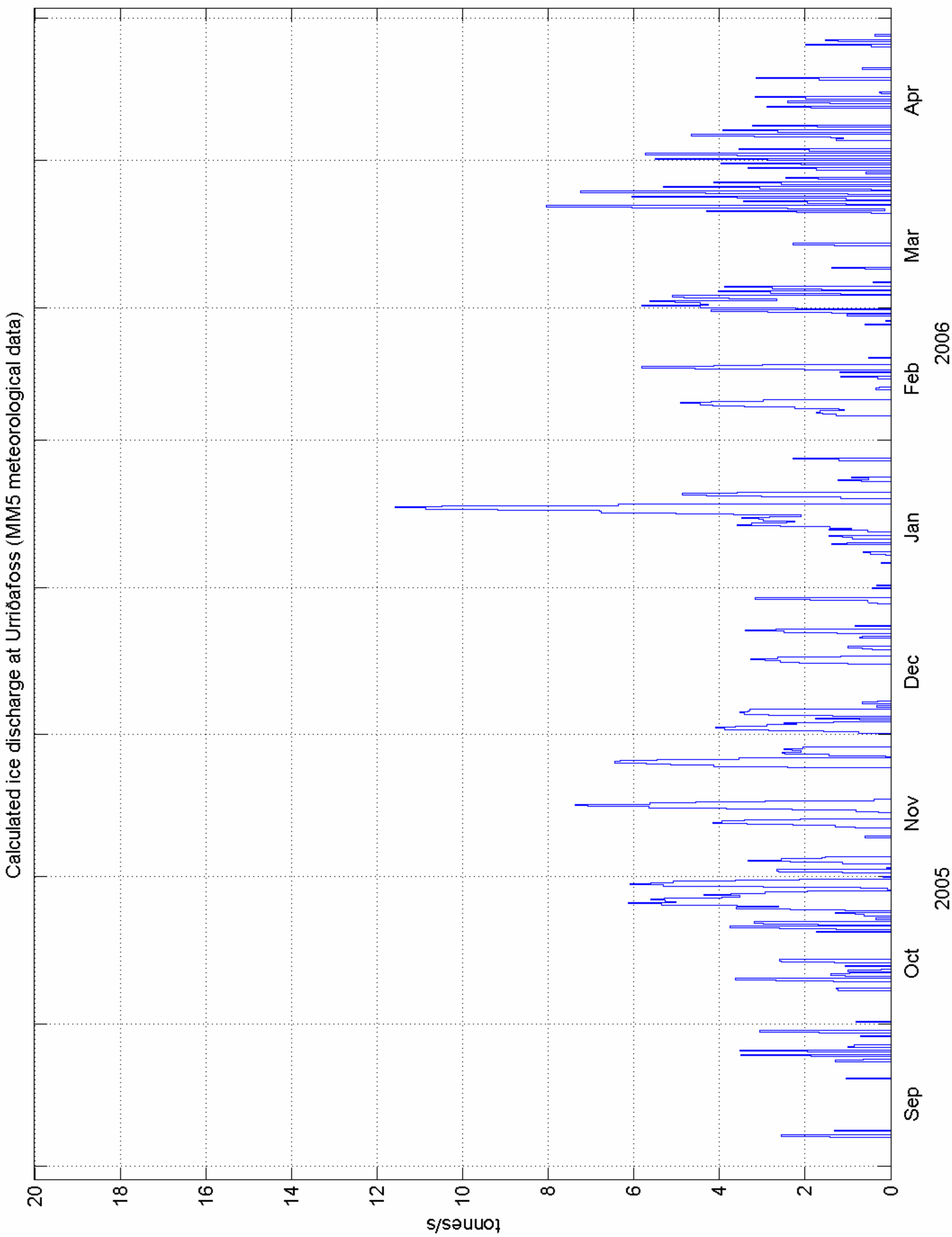
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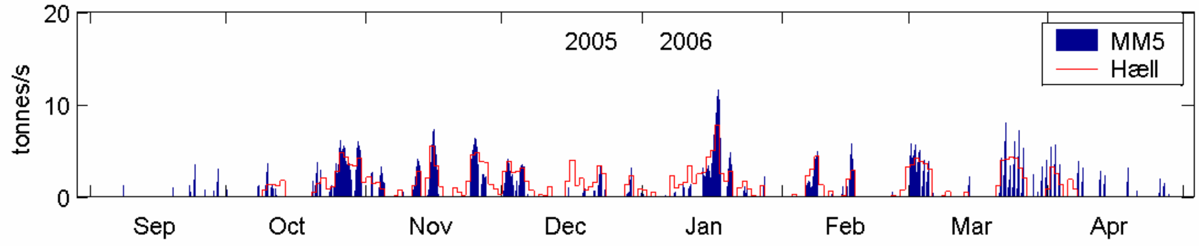
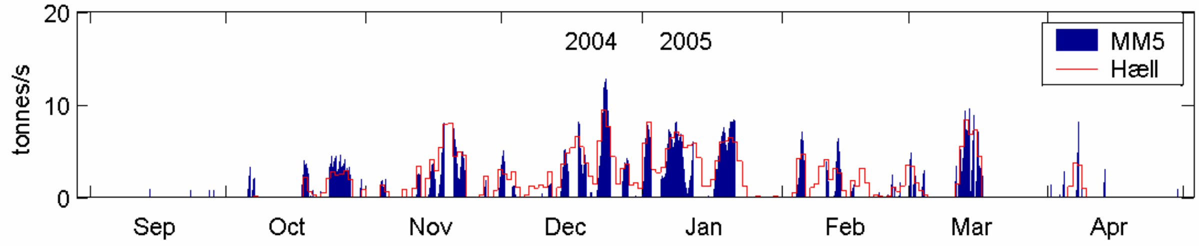
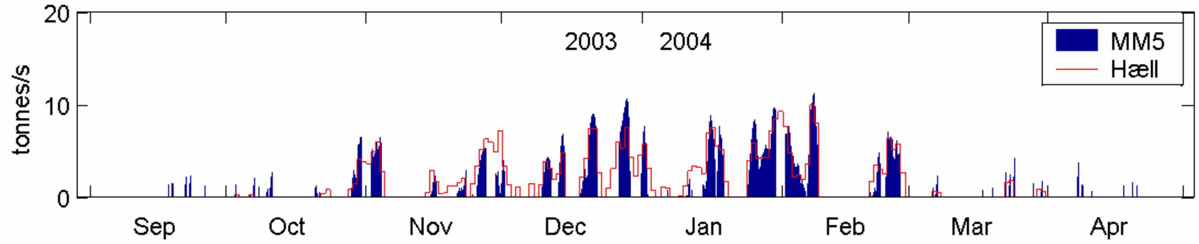
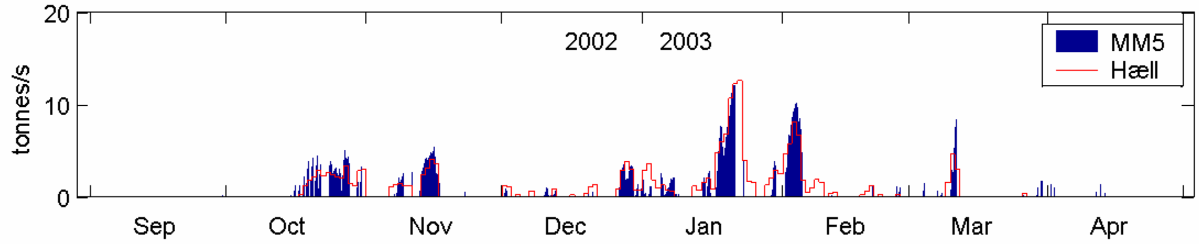
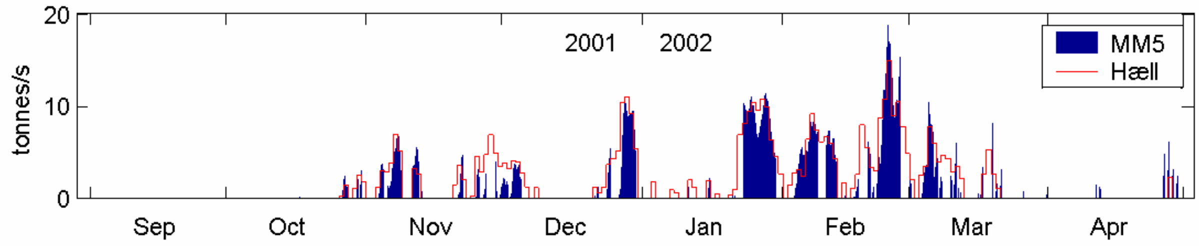
Appendix 2. **Comparison of calculated ice discharge.**

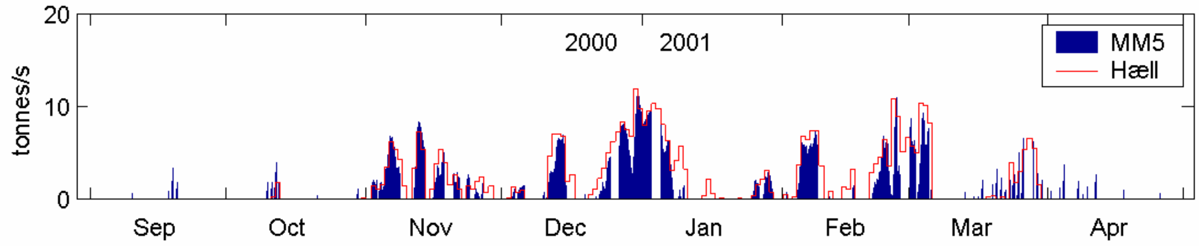




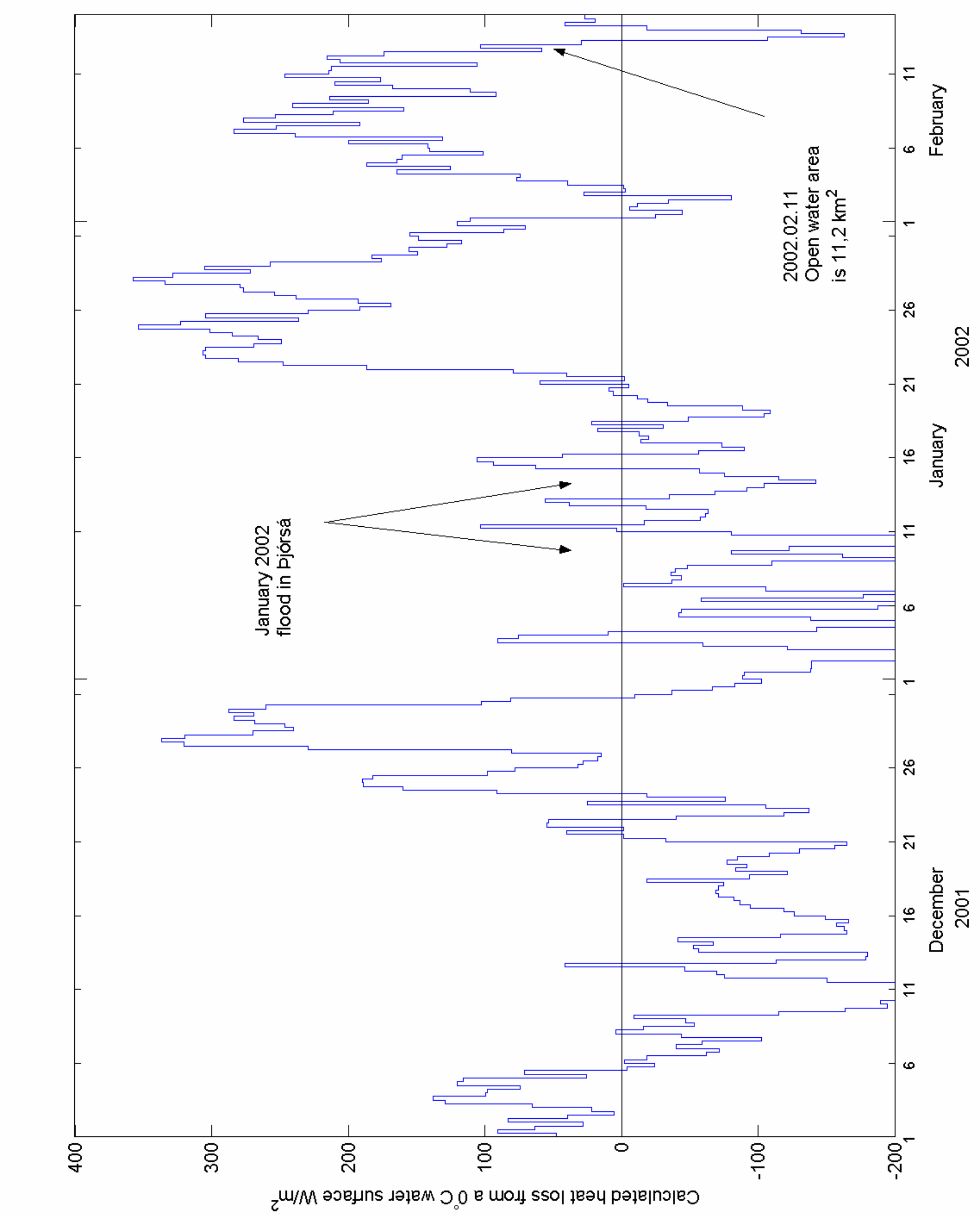


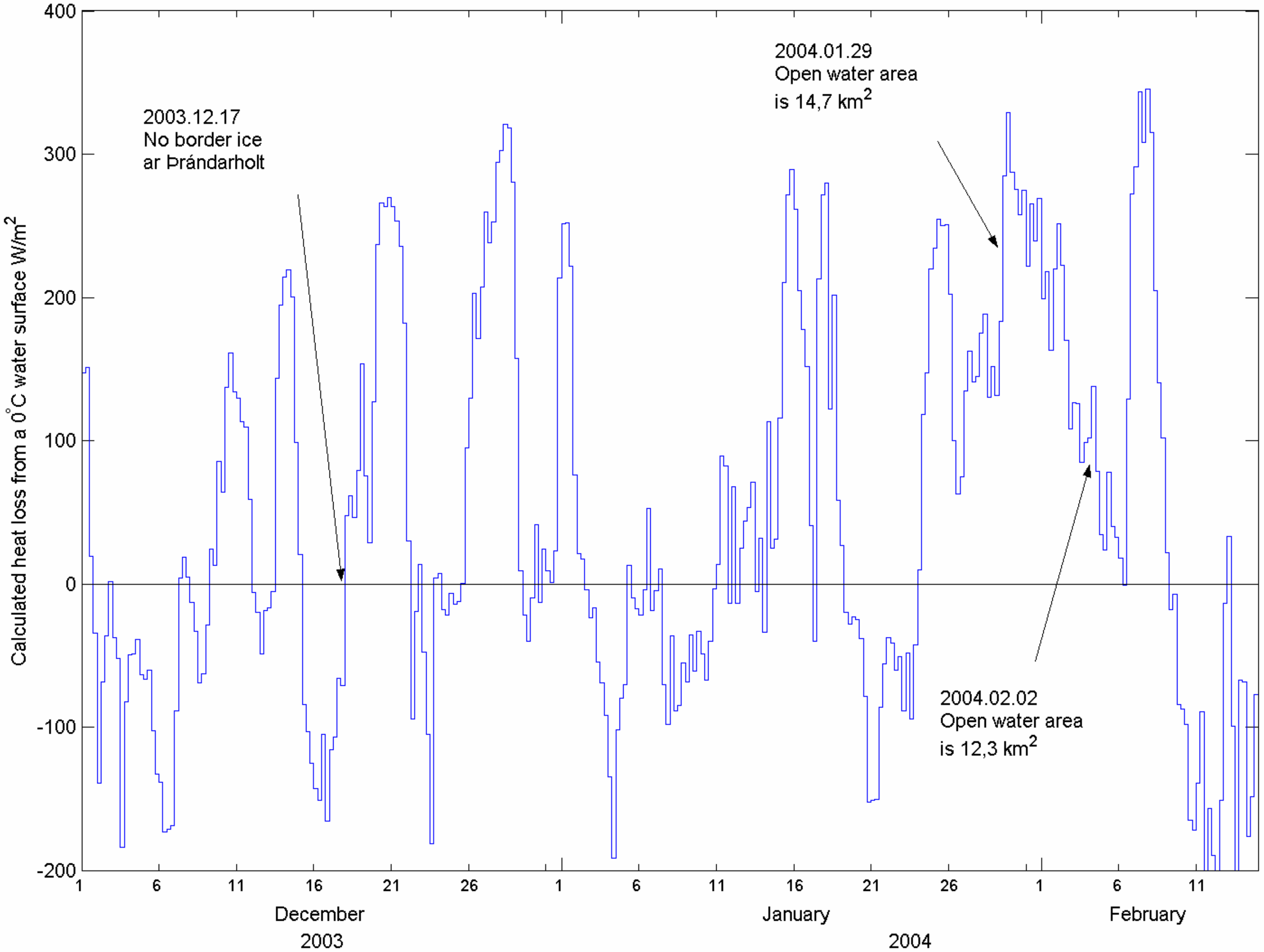




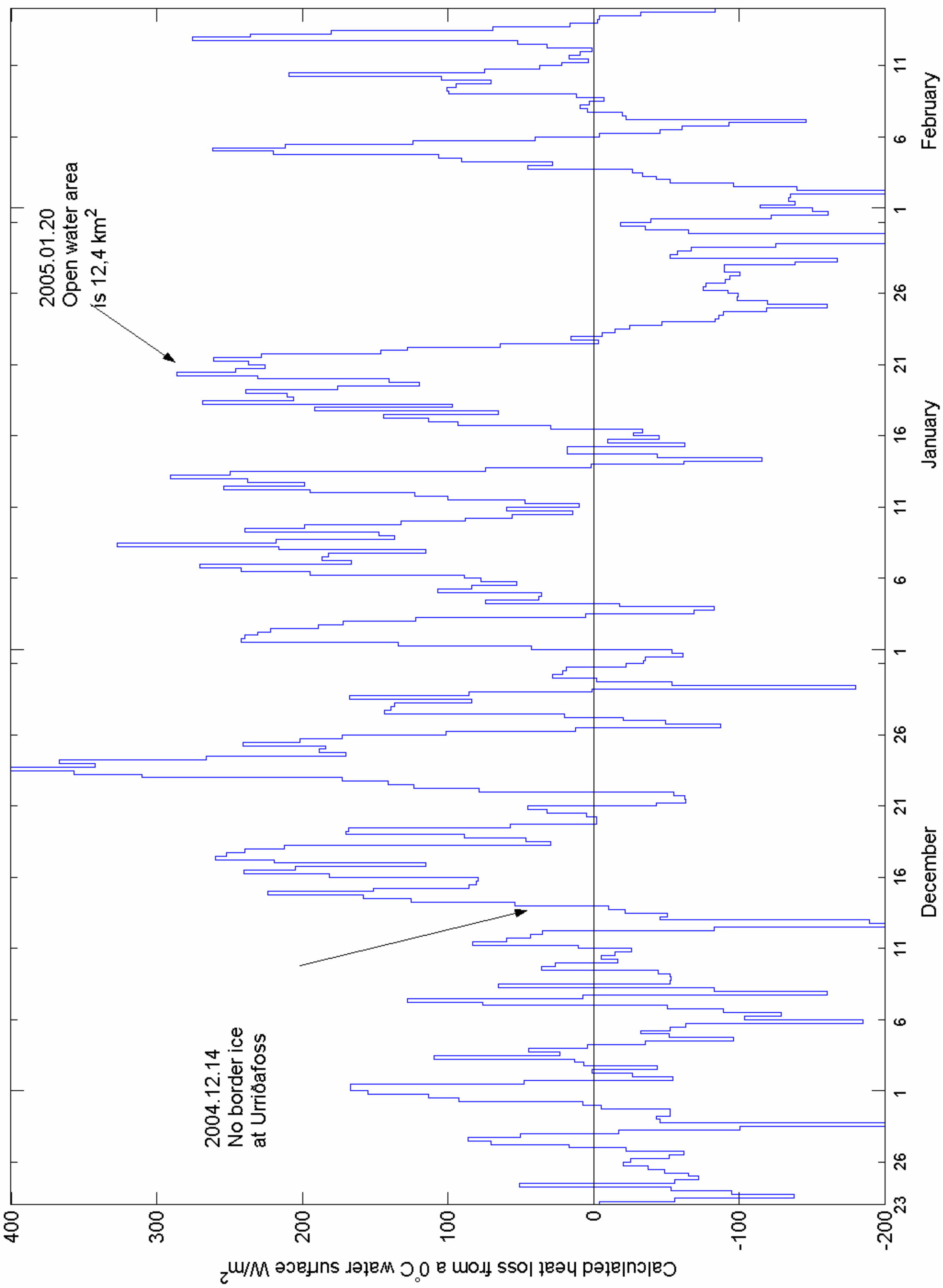


Appendix 3. Heat loss time series.





Calculated heat loss from a 0°C water surface W/m2
400
300
200
100
0
-100
-200
1
6
11
16
21
26
1
6
11
16
21
26
1
6
11
December
2003
January
2004
February
2003.12.17
No border ice
ar Þrándarholt
2004.01.29
Open water area
is 14,7 km2
2004.02.02
Open water area
is 12,3 km2

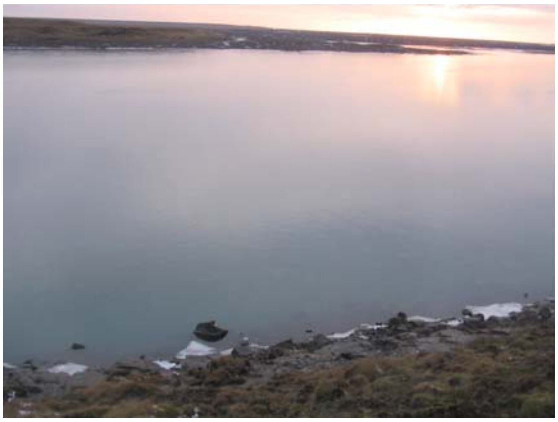


Calculated heat loss from a 0°C water surface W/m²
400
300
200
100
0
-100
-200
23
26
1
6
11
16
21
26
1
6
11
16
21
26
1
6
11
December
2004
January
2005
February
2004.12.14
No border ice
at Urriðafoss
2005.01.20
Open water area
is 12,4 km²

Appendix 4. **Automatic surveillance camera at Egilsstaðir downstream of Urriðafoss.**

December 29 2005 12:00

December 30 2005 12:00



December 31 2005 12:00

January 1 2006 12:00

January 2 2006 12:00

January 3 2006 12:00

January 4 2006 12:00

January 5 2006 12:00


January 6 2006 12:00


January 7 2006 12:00


January 8 2006 12:00


January 9 2006 12:00

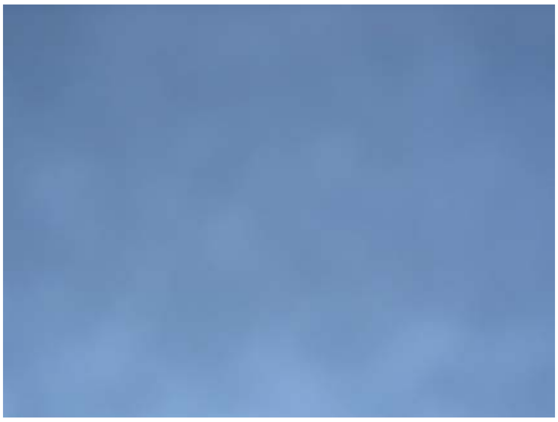

January 10 2006 12:00


January 11 2006 12:00


January 12 2006 12:00


January 13 2006 12:00


January 14 2006   12:00


January 15 2006 12:00


January 16 2006   12:00


January 17 2006 12:00


January 18 2006   12:00


January 19 2006 12:00


January 20 2006   12:00


January 21 2006 12:00

January 22 2006 12:00

January 23 2006 12:00

January 24 2006 12:00

January 25 2006 12:00

January 26 2006 12:00

January 27 2006 12:00

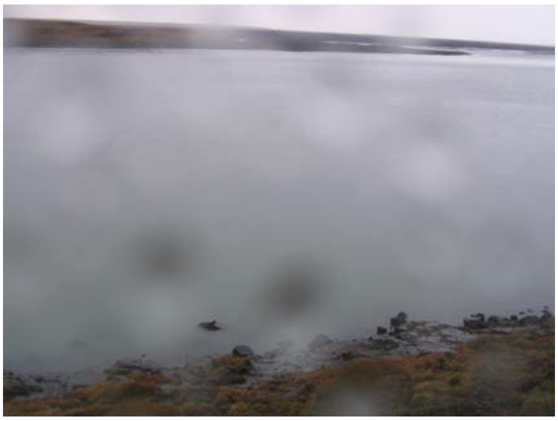
January 28 2006 12:00

January 29 2006 12:00


January 30 2006 12:00


January 31 2006 12:00


February 1 2006 12:00


February 2 2006 12:00


February 3 2006 12:00


February 4 2006 12:00


February 5 2006 12:00


February 6 2006 12:00

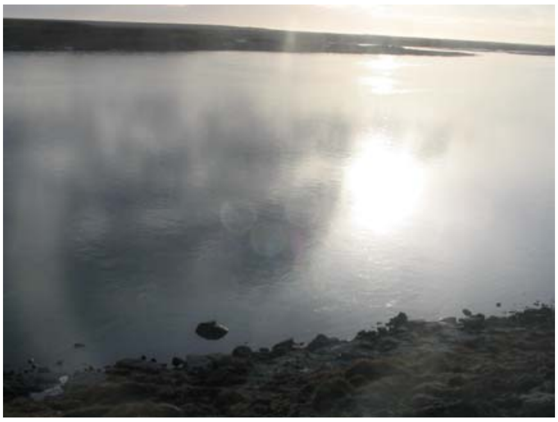

February 7 2006   12:00

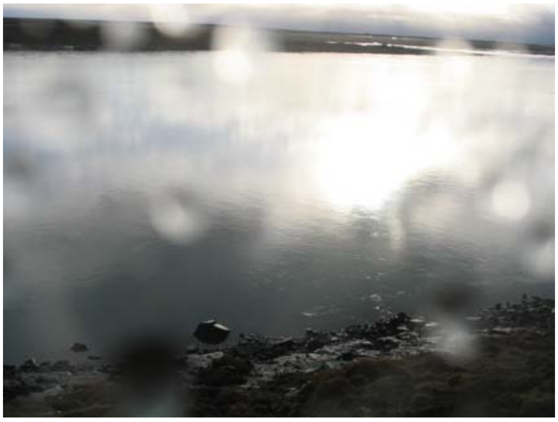

February 8 2006 12:00


February 1 2006   12:00


February 2 2006 12:00


February 9 2006   12:00


February 10 2006 12:00


February 11 2006 12:00


February 12 2006 12:00

Appendix 5. **Photographs from Þrándarholt.**

Þjórsá at Þrándarholt - ice free conditions

Border ice on February 7th 2004.

January 30th 2004. Stationary border ice covers a large part of the river along the banks, and the rest of the river is almost completely covered with slush ice. The boundary between border ice and moving frazil or slush ice can be seen quite clearly in the picture.

Appendix 6. Photographs from Urriðafoss during the winter 2004/05.

Þjórsá near U02. Ice free.

December 17 2004. Border ice several m from shore

Urriðafoss jam is advancing January 3 2005

48 hours later the upstream edge of the jam has reached U02

Urriðafoss jam just after it formed.

Shoving has created the fracture ridges seen in this picture

Appendix 7. Coordinates and elevation (ISNET93) of the MM5 grid points used.

	East [m]	North [m]	Elevation [m a.s.l.]
Reach 1	**455544**	**399816**	**214**
Reach 2	**439430**	**391910**	**126**
Reach 3	**431401**	**391963**	**95**
Reach 4	**423324**	**383996**	**57**
Hæll	**439410**	**396368**	**121**

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Heimasíða: www.lv.is