Final author comments on “A synthetic ice core approach to estimate ion relocation in an ice field site experiencing periodical melt; a case study on Lomonosovfonna, Svalbard” by C. P. Vega et al.

To the referees:
The authors truly value the general and specific comments and suggestions made by the referees which have been very helpful when revising the manuscript. We thank the time taken by the referees and we appreciate their detailed review. We agree in most of the comments made by the referees, and we have included their valuable suggestions in the revised version as long as it was possible.

Each of our responses has been noted as CV, following each of the referee’s comments.

Response to anonymous referee #1

Major comments

1. The synthetic ice core comparison to a melt-affected core is creative, but I am not convinced that the method works as intended as an indicator of ion-specific melt-induced elution. Ice core chemistry records are inherently log-normally distributed with large spikes, as shown in Figure 7, which is typical of ice core sites even unaffected by melt. Thus, the subtraction of one “spikey” record from another will inevitably lead to large positive and negative differences (see Figure 8) if the records are slightly offset in time and/or if there is any spatial variability of the chemistry data. Temporal uncertainties of at least +/- 0.1 years would be assumed for even the most well dated snowpits/cores. For example, consider a series of snow pits collected at Summit, Greenland where summer melt is extremely rare and robust seasonal changes in chemistry result in a well constrained depth-age scale. If one were to stack a series of 3 or 5 snowpits on top of one another and then subtract those values from a core collected the following year, I would hypothesize that you would see large positive and negative spikes in the difference plot (equivalent to Figure 8) even though there is no meltwater percolation present. This analysis could actually be done quite easily with the publically available data from the GEOSummit monthly snowpits and several ice cores collected at summit over the past 10 years (data available at: https://www.aoncadis.org/project/core_atmospheric_measurements_at_summit_greenland_environmental_observatory.html). I would encourage the authors to conduct this analysis at Summit as a proof-of-concept of the synthetic ice core method. In fact, Summit would be ideal because there was a single melt event in 2012 with abundant on-site observations including hourly weather data. So one could do this analysis in 2004-2011 to assess whether one sees any indication of melt elution and deposition from this method (i.e. large positive or negative difference spikes) when it is known that no melt occurred. If the method passes this initial test, then you could test the method on the 2012 melt event to see if differential elution is observed.

CV. The referee points to a very interesting test to try the method we propose. Therefore, from the snow pit dataset available online at https://www.aoncadis.org/project/core_atmospheric_measurements_at_summit_greenland_environmental_observatory.html, we selected two snowpits: one sampled on July 1st and the other one sampled in July 27th (after the melt event of July 12 2012). Since no time scales for the snowpits are published we used the density profile and the chemistry record to find an appropriate and realistic match between the series. The comparison of the density profiles is shown in Figure R1.
Figure R 1 Density profiles in the snowpits sampled at Summit in July 1st and July 27th 2012. The depth scale of the snowpit sampled in July 27th was adjusted to find a reasonable match with the density profile of the snowpit samples in July 1st.

The depth scale of the snowpit sampled in July 27th was adjusted to find a reasonable match with the density profile of the snowpit samples in July 1st. It was necessary to shift the depth profile by 3 cm which is realistic for the interval of 1 month between the sampling and the amount of water that could have melted in mid-July at the site. According to Nghiem et al. (2012), the melt event reported at Greenland on July 12th created a 2 cm ice crust at the surface of the snowpack at Summit, which is evidenced in the density profile in Figure R1 (red line). Therefore, there is no evidence of intense melt at this site that could have generated melt water that percolated further down the snowpack. Therefore, we applied our method by comparing the snowpit sampled in late July with the snowpit sampled in July 1st. Following exactly the same methodology as described in the manuscript (with the exception of using the depth scale instead of the time scale), the ion normalized concentrations in the snowpits were calculated and shown in Figure R2.

As referee nr.1 pointed out, the ion record is spiky, as expected for any record of this kind, especially if no melting and percolation occurs. We proceeded then to calculate the difference between the snowpit sampled in July 27th (analogous to the LF-11 core) and the snowpit sampled in July 1st (analogous to the LF-syn unperturbed core). We also filtered out high frequency variations using a lowpass filter (half-year moving average), as we did in the manuscript. The results are shown in Figure R3.

As it can be observed in Figure R3, the filtered series do not deviate from the mean value of the concentrations, therefore, no percolation can be inferred from them, as it can be expected to be the case for Summit during the period selected. We therefore consider that our method is applicable in Svalbard cores since it does not show false positives for the Greenland snowpits. We did not test our method in any Greenland ice core as suggested by referee nr.1 because, unfortunately, we did not find snowpit data that is already dated or a successive ice core that can be compared with the ice core data available online at the database recommended by the referee.
Figure R 2 Comparison between the snowpit samples in July 1st 2012 and the snowpit sampled in July 27th 2012. Ionic concentrations are normalized ($c_n$).
2. Summit is the ideal case, and even if the synthetic ice core method works at Summit there may be reasons why it would not work at Lomonosovfonna. The largest difficulty in my mind is that the Lomonosovfonna synthetic ice core contains no summer snow. The authors convincingly show in Fig. 6 that summer receives the least precipitation of any season, but it does receive “some”. This leads to a rather confusing situation where the synthetic core has summer values in the time series plots, even though we know that no summer snow was actually collected.

**CV.** We want to clarify that the synthetic core does contain summer snow as it can be inferred from Table 2 (there is no discontinuity in the time scale vs depth). We believe what we stated in lines 8–13 in page 5060 “This consists in building an unperturbed ice core using only the top meter snowpack record from different ice cores (top meters of the LF-08 and LF-09 cores corresponding to approx.
of the year previous to the drilling date) and the SP LF-10 snowpit, thus, constructing a snow-firm record covering over early spring, previous winter and fall of each year of the period 2007–2010 (Table 2)." is misleading since we constrained the extent of each synthetic piece to "spring, previous winter and fall" but it should say instead "...a snow-firm record covering the previous year until the date of the sampling/drilling of the previously sampled/drilled snowpit/core" as it can be corroborated in Table 2.

Continuation (Ref. 1): This will also contribute to timescale offsets that will lead to large spikes in the difference plots even without melt, as mentioned in #1 above. What is the mean ion concentrations of summer snow? If there is dry deposition or wet deposition from fog or rime then summer concentrations could be high, and their exclusion from the synthetic core would be problematic.

CV. As previously noted, summer snow has been included (Table 2); therefore, no error due to exclusion exists in our synthetic core. However, we are aware that the summer snow in the synthetic core has most probably experienced melting at each interval, i.e. in the summer of 2009, 2008 and 2007, correspondently. Since each new segment of the synthetic core starts in the spring of each year (Table 2), ions that could have been relocated from the summer layer above are not present in the new segment because they have a completely different segment origin (Table 2). We have now described this in more detail in section 2.3.

Seasonal ionic concentrations of the synthetic core are shown in Table R1.

Table R1 Seasonal ionic concentrations of ions in the LF-syn.

<table>
<thead>
<tr>
<th>Season</th>
<th>Cl</th>
<th>NO$_3^-$</th>
<th>SO$_4^{2-}$</th>
<th>Na$^+$</th>
<th>NH$_4^+$</th>
<th>K$^+$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
<th>W$_{NaMg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring (MAM)</td>
<td>25.78</td>
<td>1.05</td>
<td>5.29</td>
<td>20.73</td>
<td>2.17</td>
<td>0.43</td>
<td>2.28</td>
<td>4.89</td>
<td>0.63</td>
</tr>
<tr>
<td>Summer (JJA)</td>
<td>14.07</td>
<td>0.68</td>
<td>2.33</td>
<td>10.46</td>
<td>0.63</td>
<td>0.23</td>
<td>3.10</td>
<td>2.78</td>
<td>0.58</td>
</tr>
<tr>
<td>Autumn (SON)</td>
<td>26.74</td>
<td>1.18</td>
<td>3.89</td>
<td>22.00</td>
<td>0.61</td>
<td>0.49</td>
<td>2.74</td>
<td>4.98</td>
<td>0.65</td>
</tr>
<tr>
<td>Winter (DJF)</td>
<td>15.59</td>
<td>1.63</td>
<td>4.27</td>
<td>13.05</td>
<td>0.80</td>
<td>0.28</td>
<td>1.84</td>
<td>2.86</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Seasonal concentrations calculated in the LF-syn core are in agreement with previously reported snowpit data by Virkkunen et al. (2007) for the summit of Lomonosovfonna (2002–1999), depicting lower values during summer. Most of ions (Cl$^-$, SO$_4^{2-}$, Na$^+$, Ca$^{2+}$ and Mg$^{2+}$) show higher concentrations during summer in the LF-syn core than in the snowpit from Virkkunen et al. (2007). Seasonal $W_{NaMg}$ values in the LF-syn are much lower than the observed in the period 2002–1999 (Virkkunen et al., 2007) which contains one exceptionally warm year (2001) and long summer (2000).

Continuation (Ref. 1): Spatial variability of the chemistry between the two core sites may also make Lomonosovfonna more problematic than Summit. Table 3 shows that the 5-year smoothed records have low r values, and even several negative correlations for the same ion at different sites. Even the strongest positive correlations (p<0.05) have ~50% of common variability – and these are the 5-year smoothed values. Based on the authors’ interpretation, this cannot be due to ion elution since the ions do not elute beyond 1-2 years. Therefore, either their ion elution interpretation is incorrect, or there is large spatial variability that makes the synthetic ice core approach unviable at this site even without melt.

CV. The referee points out an interesting issue to be discussed. As described in the authors’ reply to referee nr.1 (question 5), It has been decided not to use the complete LF-08 core due to strong evidence of perturbations on the chemical record due to the presence of ice from 6.4 down to 10.6 m
(for more details, please refer to the authors’ answer to referee nr.1, question 5). This will not change the results of the LF-syn core, however, it changes part of the results previously shown in Table 3. Since the overlapping period between LF-08 and LF-09 is only between 2000–2008, we consider that a Pearson correlation is not the best way to compare how similar the ion signals are between the two cores; therefore, we used a non-parametric rank sum test (Wilcoxon) to evaluate the hypothesis that ion concentrations in the different LF-cores are samples from continuous distributions with equal medians (Table 3). Spatial variability is present at Lomonosovfonna; however, we consider that comparing cores LF-97, LF-08 and LF-09, the results presented in Table 3 (top) show a significant coherence between the ion concentrations in the different cores in the 5-year moving averages annual data. Referee nr.1 points that “…Based on the authors’ interpretation, this (low r values, and even several negative correlations for the same ion at different sites) cannot be due to ion elution since the ions do not elute beyond 1-2 years.” In the manuscript, the authors suggest that within the period 2007–2010 the relocation of ions shows no evidence of elution beyond of 2 years for most of the ions. However, we do not claim this to be the case for the period 1957–2007, in which it have been reported higher $W_{\text{NaMg}}$ values (Virkkunen et al., 2007) than in the LF-syn core. Based on the results in Table 3 we consider that using a 5 year moving average smoothing of the annual ion data is the minimum smoothing average adequate to observe the main chemical and climatic patterns in the core (Figure 2). Moreover, in the manuscript section 3.4, we also discuss the validity of using the LF-syn core to interpret ion relocation by comparing the annual mass loading of the ions in the LF-97 and LF-09 ice core and comparing them with the loadings in the LF-syn core.

3. Perhaps the strongest concern I have with this method is displayed in Figure 8 and Table 4. The authors interpret the positive peaks in Figure 8 (the LF11-synthetic plot) as indicating deposition from meltwater percolation, and negative peaks as indicating meltwater elution. They then calculate “relocation lengths” to determine the relative mobility or elution potential of each ion by finding the distance between positive (deposition) and negative (elution) peaks, as shown in Table 4. The implication mass has been eluted to the depth to which is that the measured “relocation length” represents the depth from which mass has been deposited. However, all of the "relocation lengths" are based on the distance between a HIGHER (shallower depth/more recent) deposition peak and a LOWER (deeper depth/more distant) elution peak. This does not make sense to me. Mass should be moving DOWN through the firm with the meltwater, not up. How can this "relocation length" be indicative of elution if the two peaks are not matched? In other words, the deposition peak closer to the surface must have been mobilized from higher up in the snowpack, not deeper down. One difficulty with this problem is highlighted on page 5067, lines 10-18. In this section the authors are describing the elution sequence (most easily eluted to least eluded) based on Figure 8 and Table 4. Their results suggest that nitrate is the least mobile ion. However, this does not agree with previous research at these sites, and the authors reconcile this by selecting a second deposition peak for nitrate that switches it to one of the most mobile ions. Ignoring for a moment that this deposition peak is ABOVE the elution peak and therefore in the wrong direction as described above, there is no a priori reason to select the second deposition peak for nitrate as ‘correct’ but ignore the second deposition peak for other ions like Cl, Na and Ca. This highlights a fundamental weakness with this method. How does one know *which* deposition peak matches with a particular elution (negative) peak? Certainly it makes no senses to me to pair shallower deposition peaks with deeper elution peaks. But even if deeper deposition peaks were selected, how would one choose which pair is correct? With a longer record there would undoubtedly be several possible elution-deposition peak pairs.

**CV.** The referee is right, and we have now corrected our interpretation and recalculated the percolation length. Consequently, Section 3.4 has been rewritten and Figure 8 and Table 4, modified accordingly. Basically, we corrected the difference to estimate the percolation length, which has now been calculated over the time series of the LF-11 – LF-syn results in which high frequency processes were filtered out by using a half-year moving average. We then defined four periods based in the
minima (elution) and maxima (deposition) observed in the filtered time series. In this way, high frequency variability that is superimposed to the elution-deposition signal is eliminated. Unfortunately, our synthetic ice core is truncated and it is not possible to observe a full elution/deposition cycle. However, we have estimated this, assuming a elution minimum in Period I, which allows to estimate the percolation length during Periods I–II. We consider that these results are relevant to the interpretation of ice core data from Lomonosovfonna since we estimate the temporal scale in which most of ions will most likely be affected by percolation of melt water (in this case, a lower boundary). This has the consequence that all ion information from ice cores interpreted at a resolution higher than 1 year is highly doubted to be unperturbed by percolation of meltwater. Consequently, this effect must be considered when interpreted sub-annual data.

4. The box and whisker plots in Figure 3 and 4 should show 95% confidence intervals to assess whether median concentrations in the snow, ice and firn are truly different as described in the text (see Krzywinski and Altman, 2014; http://www.nature.com/nmeth/journal/v11/n2/full/nmeth.2813.html). The reader is unable to verify the claims in Section 3.3 about differences in concentration between snow, ice and firn without these confidence intervals. Pairs with overlapping 95% confidence intervals cannot reject the null hypothesis that they are the same.

**CV.** Plots in Figure 3 and Figure 4 have now been modified to show the 95% confidence intervals (notches) according to Krzywinski and Altman (2014). We also corrected Figure 4 in which some ice samples were misclassified as firn-facies instead of as ice-facies; this correction did not change the overall boxplot results shown in Figure 4. According to Krzywinski and Altman (2014), the minimum number of data points needed to use a boxplot is n=5, consequently, we decided not to include fluoride in the boxplots since it has less than 5 samples in some of the stratigraphic units. Following the suggestions in Krzywinski and Altman (2014), we have now noted the number of samples per stratigraphic unit in Figure 3 and Figure 4. Section 3.3 has now been modified accordingly.

5. The wide range of melt percent (12-70%) values determined through the four methods does not inspire confidence in any of them. I wonder about the use of the annual average 4.4 C/km lapse rate from Pohjola et al (2002) given the work of Gardner et al. (2009) showing that summer lapse rates are higher than that of other seasons, at least in Arctic Canada.

**CV.** We have follow the work by Pohjola et al. (2002) and Claremar el al. (2012) which have used a constant lapse rate of -0.0044 °C m⁻¹ over different Svalbard glaciers (e.g. Kongsvegen, Nordenskiiöldbreen and Vestfonna). We are aware that lapse rates in certain Svalbard sites show inter-seasonal differences, with major differences ranging from +0.01 to -0.01 °C m⁻¹ (Longyearbyen) (Etzelmüller et al., 2011), and less marked differences, ranging from -0.0036 to -0.0053 °C m⁻¹ (Austfonna) and -0.0038 to -0.0051 °C m⁻¹ (Vestfonna) (Jörpeland, 2014); however, to our knowledge, such differences have not been reported for Lomonosovfonna. Considering the lapse rate values reported for Austfonna, Vestfonna (Jörpeland, 2014), and Ny-Ålesund (Wright et al. 2005) as reference, we would not expect larger inter-seasonal differences at Lomonosovfonna. Consequently, we consider that the use of an average annual lapse rate of -0.0044 °C m⁻¹ is adequate in this study.

**Continuation (Ref. 1):** The authors use the depth-density model in Figure 12 to argue for a 45% MP. However, if one were to use LF-08 instead of LF-09, one would argue for MP>70%.

**CV.** The referee points out to a very interesting issue. Density profiles of the LF-97, LF-09, LF-11 and the snowpits were obtained by measuring bulk density. On the other hand, the density profile of the LF-08 core was obtained using high resolution dielectric profiling (DEP) with a threshold value of 900 kg m⁻³, i.e. values above that were set to NaNs. Anomalous elevated density values are a consequence of the interaction between the firm permittivity and conductivity and are recognized to be
a problem in the method, leading generally to exaggerated estimates of the density. The deviation of the density profile of the LF-08 compared to the LF-09 and LF-11 cores occurs at an approximate depth of 6.4 m (corresponding to the year 1999.8 in the time scale). By inspecting the photos taken to the LF-08 core, ice is observed from 6.4 m down the core, with absence of firn. This is not registered in the LF-09 core (the LF-11 core only covers until 2004) or in the snowpits obtained by Virkkunen et al. (2007). The photographs of the LF-08 core show that the ice from 6.4 m and further deep until the end of the core at 10.6 m, is anomalously clear, i.e. it is not firn that has been soaked with meltwater. Members of the team that drilled the LF-08 core have noted that there were many crevasses observed at the site during 2008; consequently, the most feasible explanation to this clear ice section of the core is that at the depth of 6.4 m the team drilled into a water-filled crevasse, and therefore, the LF-08 core has not preserved the atmospheric signal from 6.4 m deep. This is also observable in the water stable isotope record which shows a lower seasonal amplitude between 6.4 m and the end of the core, compared with the top section. We consider that the ice found in the LF-08 was not formed due to a simple melt-percolation-refreezing event. If this would have been the origin of the ice column, we should expect to observe such intense event in the other Lomonosovfonna records; however, this signal is absent. Therefore, we have used the LF-08 record only down to 6.4 m in this study. This will not change the results of the LF-syn core since only the top part of the LF-08 was used to construct the synthetic core. Figures 2, 5 and 12 have been re-made accordingly. Table 3 has been also corrected including core LF-08 only down to 6.4 m. Sections 2.2 and 3.1 have been modified accordingly.

6. I have difficulty accepting some of the authors’ key conclusions: (a) that “using 5 year moving averages of the ionic data allows having comparable records when different ice cores are used”, and “we estimate that the atmospheric ionic signal remains preserved in recently drilled Lomonosovfonna ice cores at an annual or bi-annual resolution.” The negative correlations between 5-year smoothed LF-08 and LF-09 records in Table 2 and the corresponding differences between the 5-year smoothed records in Figure 2 contradict this statement.

CV. Please refer to response to referee nr.1, question 2.

Continuation (Ref. 1): (b) “we reiterate that the different ice core records from Lomonosovfonna all share the same climatic and chemical features...” See (a) for the “chemical features” part, and the large differences in density with depth between LF-08 and LF-09 shown in Figure 12 are not consistent with assertion of the same climate conditions.

CV. Please refer to response to referee nr.1, question 5.

Minor comments

Continuation (Ref. 1): P. 5056 line 18: Missing word “it” between “making” and “difficult”

CV. The word “it” has been added.

Continuation (Ref. 1): P. 5057 lines 27-28: I’m unclear about the meaning of “about 25 to 55% of the annual accumulation... suffered melt”. Does that mean that each year 25 – 50% of the annual snowpack is converted to liquid water and percolated down into the underlying snow/firn? Or does it mean that 25-50% of the annual snowpack is affected by meltwater percolation? I suspect the authors mean the former, but please clarify.

CV. The sentence means that 25 to 50 % of the annual accumulation may melt and percolate into the firn. We have corrected the sentence in the manuscript and now says: “Pohjola et al. (2002) found that at Lomonosovfonna, about 25 % to 55 % of the annual accumulation over the 20th century may melt and percolate into the underlying snow/firn.”
Continuation (Ref. 1): P. 5060 line 3: “scaling” should be “weighing”  
CV. Corrected.

Continuation (Ref. 1): P. 5060 line 8: “consists in” should be “consists of”  
CV. Corrected.

Continuation (Ref. 1): P. 5060 line 9: “top meter snowpack record from different” should be “top meter OF THE snowpack from different” (insert “of the”; delete “record”)  
CV. Corrected.

Continuation (Ref. 1): P. 5061 line 3: “snow as function” should be “snow as a function”  
CV. Corrected.

Continuation (Ref. 1): P. 5061 line 6: delete comma after“(2013)”  
CV. Corrected.

Continuation (Ref. 1): P. 5062 line 11: “description on” should be “description of”  
CV. Corrected.

Continuation (Ref. 1): P. 5062 lines 14-15: Is the automated d18O cycles counting routine published or described in detail anywhere? This is not trivial, especially in a melt-affected site  
CV. This routine has been first proposed, described and applied to LF-cores by Pohjola et al. (2002). We basically applied the same routine in the ice cores LF-08, LF-09 and LF-11. Additionally, results obtained for the LF-09 core were cross checked with visual δ18O cycles counting and volcanic horizons (Vega et al. 2015b).

Continuation (Ref. 1): P. 5063 line 8: The equation is not necessary – this is generally well known.  
CV. We have decided to leave Eq.(1) for the moment to avoid any lack of information about the normalization process. If Eq.(1) is considered to be unnecessary in the text, we are open to remove it in a later state of the manuscript.

Continuation (Ref. 1): P. 5063 line 12: “associated to” should be “associated with”  
CV. Corrected.

Continuation (Ref. 1): P. 5063 line 13: “uncertainty on” should be “uncertainty of”  
CV. Corrected.
Continuation (Ref. 1): P. 5063 lines 23-25: Are the 95% significance values corrected for the reduced degrees of freedom introduced by the 5-year smoothing? Please clarify and be sure to do this if not already done.

CV. The significance values in Table 3 were not corrected for the reduced degrees of freedom introduced by the 5-year smoothing. We have now corrected the values using a table of critical values for Pearson’s r and a level of significance for a two-tailed test. This has now been described in Table 3.

In view that the interpretation of the LF-08 core has now been restricted between 2000–2008, we have decided to apply a non-parametric test to compare cores LF-08 and LF-09 in Table 3 instead of the Pearson coefficients. Therefore, we used the Wilcoxon rank sum test to test the null hypothesis that data in the LF-08 and LF-09 cores are samples from continuous distributions with equal medians, against the alternative that they are not. We have included the results in Table 3.

Continuation (Ref. 1): P. 5065 line 2: “melting is most probably confined to a particular time period” is a truism. Everything is confined to a particular time period – what is the time period? I’m unsure of the point the authors are making here.

CV. The sentence was indeed unclear. We have now changed it to “Positive $W_{NaMg}$ values indicate that melting has most probably occurred”.

Continuation (Ref. 1): P. 5066 line 8: “Having in mind” should be “Keeping in mind”

CV. Corrected.

Continuation (Ref. 1): P. 5066 lines 14-15: I don’t understand the statement “To avoid any bias for the snow accumulated after the spring 2010 and 2011 this period was not considered in the normalization of the LF-11 ionic concentrations”. This seems like it could be relevant to my point #2 above, but this should be clarified and expanded upon.

CV. As Mentioned in the manuscript text and in Table 2, the top part of the LF-11 core (0–0.6 m w.e.) was not used to construct the LF-syn core, therefore, we did not contemplate this section of the LF-11 core when we normalized the ion data. We have now written in section 3.4: “Since the top part of the LF-11 core (0–0.6 m w.e.) was not used to construct the LF-syn core (Table 2) and to avoid any bias caused for the snow accumulated after the spring 2010 and 2011, this period was not considered in the normalization of the LF-11 ionic concentrations.”

Continuation (Ref. 1): P. 5066 line 17: “associated to” should be “associated with”

CV. Corrected.

Continuation (Ref. 1): p. 5067 line 24: “ice layer” should be plural

CV. Corrected.

Continuation (Ref. 1): p. 5068 line 8: What about the minimum in 1982, which is larger than the minimum in 1995 (Fig 10)? I disagree with the statement that “both approaches” show a minimum around 1995.
CV. We agree with the referee; the sentence should have been removed at an earlier stage of the manuscript. The sentence has now been removed since what we want to emphasize in the paragraph is that the production of meltwater at Lomonosovfonna has increased during the 1989–2010 rather than pin-point particular maxima or minima.

Continuation (Ref. 1): P. 5068 lines 11-12: I disagree that figure 11 shows “stable values” of melting. How can the values be “stable” and also have “alternating warm and cold years”. The latter description is more appropriate.

CV. The sentence has been corrected accordingly. It now says: “When considering the period between 2007–2010 (Figure 11), the melting shows alternating warm and cold years…”

Continuation (Ref. 1): P. 5069 line 17: Avoid using qualitative statements like “moderate melting”. How much melting is a “moderate” amount?

CV. A “moderate melting” could be assumed to be less than 50% of the annual snowpack, but of course this is completely arbitrary. Consequently, we have now removed the term “moderate” from the manuscript. The sentence now says: “However, the calculated MPs using the PDD approach and the snow-energy do not agree with the results obtained by the synthetic core approach which suggest that melting during the 2007–2010 period has not been high (i.e < 50 %) which is also supported by the stratigraphy observed in the LF-09 and LF-11 cores (Figure 9).”

Continuation (Ref. 1): P. 5071 line 18: I disagree that it is a “fact” that “ion relocation took place a moderate depths”. This is your hypothesis, but not a fact.

CV. The referee is right. We have changed the word “fact” for “hypothesis” in the line.

Response to anonymous referee #2

Major comments

1. In the latter part of 3.4 Synthetic ice core, the authors estimated relocation length of ion species from the distance between maximum (deposition) peaks and minimum (elution) peak in Figure 8. When surface melting occurs, melt water washed out the ion species from initial depth to deeper depth. Therefore, elution peaks should appear above deposition peaks. However, elution peaks of all ion species appeared below deposition peak in Figure 8. Consequently, the distances between elution peaks and deposition peaks in Figure 8 are not relocation length. The authors should clarify their discussions about the relocation length. In addition, I could not understand the reason why the secondary relocation length was adopted for only nitrate.

CV. The referee is correct. We have now corrected our interpretation and recalculated the percolation length. Consequently, Section 3.4 has been rewritten and Figure 8 and Table 4, modified accordingly. Basically, we corrected the difference to estimate the percolation length, which has now been calculated over the time series of the LF-11 – LF-syn results in which high frequency processes were filtered out by using a half-year moving average. We then defined four periods based in the minima (elution) and maxima (deposition) observed in the filtered time series. In this way, high frequency variability that is superimposed to the elution-deposition signal is eliminated. Unfortunately, our synthetic ice core is truncated and it is not possible to observe a full elution/deposition cycle. However, we have estimated this, assuming a elution minimum in Period I, which allows to estimate the percolation length during Periods I–II. We consider that these results are relevant to the interpretation of ice core data from Lomonosovfonna since we estimate the temporal scale in which most of ions will most likely be affected by percolation of melt water (in this case, a lower boundary).
This has the consequence that all ion information from ice cores interpreted at a resolution higher than 1 year is highly doubted to be unperturbed by percolation of meltwater. Consequently, this effect must be considered when interpreted sub-annual data.

2. The authors estimated amount of melt water product from PDD estimation, snow-energy model and snow densification model in the chapter 3.5. I suggest that the discussion about the comparisons of these values to melt water product estimated by ion relocation behaviors such as melt index should be included in this chapter. The authors mentioned them only in abstract, but did not describe the details of the estimation in text and conclusions. I believe that the evaluation of melt product estimated by the profiles of ion species is important information to develop the studies of “wet ice core”.

CV. We have the following paragraph in section 3.5: “Figure 13 shows a comparison between the LF-11 and the LF-syn ice core depth–time scale. It is clear from Figure 13 that the depth differences between the ice cores (black and grey lines) can be related to a partial melting of the snowpack and refreezing of the meltwater taking place between the 2007–2011 period, as evidenced by the ionic relocation. An estimate of the decrease in depth of the LF-syn ice core by the effects of snowpack melting considering a MP = 20, 30, 48 and 70 % during 2007–2010 as suggested by the firm-densification model, MPs obtained using the PDD approach (using instrumental temperatures) and the snow-energy model is shown in Figure 13. It can be observed that a MP = 20–30 % results in a LF-syn ice core depth-time scale highly similar to the depth-time scale of the LF-11 ice core during the 2007–2010 period, confirming that the MP during that period is coherent with the results of the firm-densification model but not with the PDD results shown in table Table 5.” We think that this is what the referee is asking for; otherwise, we would be pleased to get a clarification of what the referee intended that we describe in more detail.

Minor comments
In chapter 3.2 and Table 3, the authors showed that the correlation coefficients in LF-08 and LF-09, and it was different from that in LF-97 and LF-08. The authors should describe discussion about the results, and relations of the result to the subject of this study.

CV. Table 3 has now been modified in view of the LF-08 reduced record used in the manuscript (for more info, please refer to the reply to questions 5 and 2 of referee nr.1). Section 3.2 has been modified accordingly.

Continuation (Ref. 2): I could not read how the authors estimated the snow accumulation by LF-syn core in Figure 6 right. Please describe the details of the estimation.

CV. We have now added the following sentence in section 3.4: “The snow accumulation in the LF-syn core was calculated as the length (in m w.e.) between two LF-syn samples which in average represent 1.2 months of accumulation.” In addition, the Y-axis legend in Figure 6 (right) and the X-axis legend in Figure 6 (left) have been added.

Continuation (Ref. 2): Geographical name (Sveagruva and Nordenskiöldbreen) should be described in the map of Figure 1.

CV. Figure 1: it has been now corrected to include the geographical locations of Sveagruva and Nordenskiöldbreen.

Continuation (Ref. 2): P.5063 L. 16:”LF-09 and LF-09”→ “LF-08 and LF-09”

CV. This has been corrected accordingly.
Continuation (Ref. 2): Table 3: Description about the bottom table (LF-08 and LF-09 ice cores) should be added.

CV. Description about the bottom table (LF-08 and LF-09 ice cores) has now been included accordingly.

References


Virkkunen et al. 2007. Warm summers and ion concentrations in snow: comparison of present day with Medieval Warm epoch from snow pits and an ice core from Lomonosovfonna, Svalbard. J. Glaciol., 53(183), 623–634.

A synthetic ice core approach to estimate ion relocation in an ice field site experiencing periodical melt; a case study on Lomonosovfonna, Svalbard

C. P. Vega,¹ V. A. Pohjola,¹ E. Beaudon,²,* B. Claremar,¹ W. J. J. van Pelt,¹ R. Pettersson,¹ E. Isaksson,³ T. Martma,⁴ M. Schwikowski,⁵ and C. E. Bøggild⁶,§

[1]Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala, Sweden
[2]Arctic Centre, University of Lapland, 96101 Rovaniemi, Finland
[3]Norwegian Polar Institute, Fram Centre 9296 Tromsø, Norway
[4]Institute of Geology, Tallinn University of Technology, 19086 Tallinn, Estonia
[5]Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
[6]The University Centre in Svalbard, UNIS, Pb. 156 9171, Longyearbyen, Norway
[*]now at: Byrd Polar and Climate Research Center, 082A Scott Hall, 1090 Carmack Road, Columbus, OH 43210-1002, USA
[§]now at: Arctic Technology Centre, Technical University of Denmark, Kemitorvet, Bygning 204, 2800 Kgs. Lyngby, Denmark

Correspondence to: C. P. Vega (carmen.vega@geo.uu.se)

Abstract

Physical and chemical properties of four different ice cores (LF-97, LF-08, LF-09 and LF-11) drilled at Lomonosovfonna, Svalbard, were compared to investigate the effects of meltwater percolation on the chemical and physical stratigraphy of these records. A synthetic ice core approach was employed as reference record to estimate the ionic relocation and meltwater percolation length at this site during the period 2007–2010. Using this method, a partial the ion elution sequence obtained for Lomonosovfonna was NO₃⁻SO₄²⁻>NO₂⁻>NH₄⁺>Mg²⁺>Cl⁻. K⁺, Na⁺>Ca²⁺—with acidic ions nitrate being the most mobile within the snowpack. The relocation length of most of the ions was in the order of 1 m, with the exception of SO₄²⁻ showing relocation lengths >2 m during this period. In addition, by using both a positive degree day (PDD) and a snow-energy model
approaches to estimate the percentage of melt at Lomonosovfonna, we have calculated a melt percentage (MP) of the total annual accumulation within the range between 48 and 70 %, for the period between 2007 and 2010 which is above the MP range suggested by the ion relocation evidenced in the LF-syn core (i.e. MP = 30%). Using a firm-densification model to constrain the melt range, a MP of 30 % was found over the same period which is consistent with the results of the synthetic ice core approach, and a 45 % of melt for the last 60 years. Considering the ionic relocation lengths and annual melt percentages, we estimate that the atmospheric ionic signal remains preserved in recently drilled Lomonosovfonna ice cores at an annual or bi-annual resolution when weather conditions were similar to those during the 2007–2010 period.

Key words: ion relocation, percolation length, melt index, ice cores.

1 Introduction

Pollutants produced in low- and mid-latitudes are transported to the polar regions where they are included in the snow by different mechanisms, mainly wet and dry deposition, accumulating in glaciers and ice caps. Major ions, such as SO$_4^{2-}$, NO$_3^-$, Na$^+$, and Cl$^-$, are deposited in the snowpack and can be measured in ice cores, providing valuable information about their sources, chemical transformations in the atmosphere, and transport patterns to the sampling site (Laj et al., 1992; Goto-Azuma and Koerner, 2001; Kekonen et al., 2002; Hastings et al., 2004; Hastings et al., 2009). Nitrate (NO$_3^-$), for example, has been used as a record for past atmospheric nitrogen oxides (NO$_x$ = NO$_2$ + NO) (Kekonen et al., 2002; Röthlisberger et al., 2002; Hastings et al., 2005; Hastings et al., 2009; Vega et al., 2015b).

However, this proxy has been difficult to develop since NO$_3^-$ in snow has several sources and experiences post-depositional processes, such as photolysis, diffusion within the ice, evaporation as HNO$_3$, or relocation by meltwater (Goto-Azuma et al., 1994; Honrath et al., 1999; Rempel et al., 2002; Röthlisberger et al., 2002). The latter has been an enigma to potential ice core sites since relocation and preferential elution of chemical species gives an altitudinal and latitudinal threshold for potential drilling sites. To make use of environmental data from outside the dry snow zones on glaciers in the polar areas, it is important to give better regional coverage of the atmospheric chemistry outside the large polar ice sheets. For a correct interpretation of the chemical ice core data from drilling sites where significant summer melting occurs, it is necessary to estimate the post-depositional effects of meltwater percolation on the chemical content of snow and ice.
It is known that most of the ice core drilling sites at Svalbard experience summer melting, which may damp the chemical signal of ionic species, making it difficult to understand the transfer function between ion concentrations in the atmosphere and the snow (Goto-Azuma et al., 1994; Isaksson et al., 2001; Moore et al., 2005; Grinsted et al., 2006). Ions do not move uniformly when are removed from the snowpack by meltwater. Instead, they are released following a preferential elution (Goto-Azuma et al., 1994; Eichler et al., 2001; Ginot et al., 2010). The elution of ions is a consequence of sequential grain-scale processes during dry metamorphism (Brimblecombe et al., 1985; Schöndorf and Herrmann, 1987; Goto-Azuma et al., 1994) and also influenced by the pH of meltwater (Goto-Azuma et al., 1994). Moore and Grinsted (2009) calculated the elution factors ($e$) of several ions present in snow and ice from an ice core drilled at Lomonosovfonna, Svalbard during 1997 (LF-97). According to their results, the most mobile species in the snow were Ca$^{2+}$, Mg$^{2+}$, SO$_4^{2-}$ and NO$_3^-$ with Na$^+$, Cl$^-$, NH$_4^+$ and K$^+$ being eluted later. The elution sequence changed slightly in ice, where NO$_3^-$ is the most mobile specie and Mg$^{2+}$ the latest ion to elute. Moore and Grinsted (2009), Ginot et al. (2010) and Eichler et al. (2001) results point to the ionic charge as the control factor in the elution process instead of the acidic character of the ion as reported by Brimblecombe et al. (1985) and Goto-Azuma et al. (1994).

The special characteristics of snow and firm properties on high altitude ice fields with heterogeneous stratigraphy as Lomonosovfonna are a consequence of the long winter season with air temperatures below the freezing point, enhanced snow drift by strong winds, relatively low annual snow accumulation and cold ground surfaces, punctuated by intermittent melt events. The interaction between the meltwater front formed during episodic melt events and the different stratigraphic horizons form preferential flow patterns and create a secondary stratigraphy if refreezing takes place within colder layers (Colbeck, 1991). The secondary stratigraphy produced by refreezing water will have a large influence in meltwater flow and discharge (Bøggild, 2000). During the intermittent melt periods, dislocation of water from more superficial layers percolates into the deeper stratigraphy routed as preferential meltwater flow and the formation of solute enriched ice layers during refreeze of the percolated water will affect the chemistry (i.e. ionic concentrations in this study) recorded in ice cores drilled at the high altitude ice fields of Svalbard.

One estimate to measure if snow melting and percolation have occurred in an ice core stratigraphy is to construct an ion ratio, based on the selection of a pair of ions that originate
from the same source but have dissimilar elution coefficients, e.g. \( \text{Na}^+ / \text{Mg}^{2+} \) and \( \text{Cl}^- / \text{K}^+ \) as reported by Iizuka et al. (2002) and Grinsted et al. (2006). Using the logarithms of the different ionic ratios as melt indices, denoted as \( W_{\text{NaMg}} \) or \( W_{\text{ClK}} \) depending upon the pair of ions selected, a reconstruction of the melting history of a particular ice core site can be reconstructed (Grinsted et al., 2006). Pohjola et al. (2002) found that at Lomonosovfonna, about 25% to 55% of the annual accumulation over the 20th century may melt and percolate into the underlying snow/firn-covered melt, with meltwater percolating through the snowpack during warm summers. The most mobile ions reported by Pohjola et al. (2002) were \( \text{NO}_3^- \) and \( \text{SO}_4^{2-} \), which presented ~50% higher concentrations in ice compared with firn layers. On the other hand, \( \text{NH}_4^+ \) presented an even distribution between firn and ice. A percolation mechanism was proposed to have an important role in the redistribution of this specie in the ice crystals after deposition. Pohjola et al. (2002) concluded that although some ions may have had a high mobility within the upper part of the LF-97 ice core (0–36 m deep) during anomalously warm summers, the signal was still identifiable, being retained within an annual or biannual resolution.

The aim of this work is to study the temporal change of the snow/firn chemical and physical stratigraphy on the ice field Lomonosovfonna, Svalbard. In this study we will use data from shallow ice cores and snow pits repeatedly studied in 2008, 2009, 2010 and 2011 at Lomonosovfonna to investigate the temporal and vertical change in the stratigraphy and ion composition of the snow/firn column. To manage the sequential change in ion concentrations we will create a synthetic ice core using the top layer (~1 year accumulation) of different shallow ice cores and snowpits to have a reference record to assess the relocation of major ions by meltwater and the percolation length at the site during recent years. In addition, the melt percentage of the annual accumulation at Lomonosovfonna is obtained by using a positive degree day and a snow-energy model approach, and used together with the synthetic core to infer the effects of meltwater on the ionic signals present in recent ice cores drilled at Lomonosovfonna.

2 Methods

2.1 Study sites

Four ice cores (LF-97, LF-08, LF-09 and LF-11) and a 1.50 m deep snowpit (SP LF-10) were considered in this study, all retrieved at the Lomonosovfonna ice cap, which is one of the highest glaciated areas in Svalbard with an elevation of ~1250 m a.s.l. (Isaksson et al., 2001;
Beaudon, 2012; Vega et al., 2015b) (Figure 1). Lomonosovfonna is located northeast of Longyearbyen, which is the largest settlement in Svalbard, and Pyramiden, a smaller settlement where coal mining activities were carried out until 1998. Two of the ice cores (LF-97 and LF-08) were drilled at the highest point of the ice cap ca. 100 m apart from each other, while the LF-09 and LF-11 ice cores were drilled ca. 4.5 km east-south-east from the site cored in 1997 and 2008 (Figure 1, Table 1).

2.2 Sampling and analyses

The cutting, sampling and chemical analyses of the LF-97 and LF-08 ice cores are reported by Kekonen et al. (2005, and references therein) and Beaudon (2012), respectively. The LF-09 and LF-11 ice core cutting and SP LF-10 sampling were done in clean conditions, wearing clean overalls, face masks and powder free gloves. All materials employed to collect the samples were rinsed with ultra-pure water (18 MΩ) and kept in clean plastic bags. Ions were quantified using a Metrohm ProfIC 850 ion chromatographer. Samples and standards were melted and handled under laminar flow hood (class 100) to minimize any contamination from the laboratory environment. Samples and standards were placed in the auto-sampler covered with aluminium foil to avoid any dust contamination. Three sample blanks (made of ultra-pure water) were analysed at the beginning and the end of every batch. Sample checks (bulk-snow from Ny-Ålesund or Uppsala) were analysed every ten samples to ensure the replicability of the measurements within a batch. The analytical error was below 5 % for each ion. Detection limits (D.L.) for each ion were calculated as the average value of six blanks plus 1.68 times the standard deviation (σ) of the six measurements (i.e. D.L. = average blank + 1.68 × σ blank), being below 0.3 μeq L⁻¹ for all ions.

Water stable isotopes (δ¹⁸O-H₂O) were analysed at the Institute of Geology at Tallinn Technical University, Estonia. The measurements were done with a Picarro L2120-i water isotope analyser (cavity ringdown spectroscopy technology) with a high precision vaporizer A0211. All isotope measurements were calibrated in a two-point scale against the international standards VSMOW (Vienna Standard Mean Ocean Water) and VSLAP (Vienna Standard Light Antarctic Precipitation). The reproducibility of replicate analysis for δ¹⁸O-H₂O measurements was estimated to be ± 0.1 ‰.

The ice layer and grain size were inspected in each core section by visual examination on a lighted bench located in the cold laboratory (−20 °C) at the Norwegian Polar Institute. Bulk
density was calculated by weighing and measuring each ice core piece of the LF-97, LF-09 and LF-11 cores. Density in the LF-08 core was estimated using high resolution dielectric profiling (DEP) with a threshold value of 900 kg m$^{-3}$, i.e. values above that were set to NaNs. The stratigraphic melt index was calculated as the percentage of clear ice present in the ice core (considering the ice core length in m w.e. (m water equivalent)).

2.3 Synthetic ice core construction

In order to estimate the effects of meltwater percolation on the chemical record at Lomonosovfonna, a synthetic ice core approach was implemented. This consists of building an unperturbed ice core using only the top meter of the snowpack from different ice cores (top meters of the LF-08 and LF-09 cores and the SP LF-10 snowpit), thus, constructing a snow-firm record covering the previous year until the date of the sampling/drilling of the previously sampled/drilled snowpit/core during the period 2007–2010 (Table 2). Consequently, summer snow has been included in the synthetic core (Table 2); therefore, no error due to exclusion of this layer is present in the time scale. However, the summer snow in the synthetic core has most probably experienced melting at each interval, i.e. in the summer of 2009, 2008 and 2007, correspondently. Since each new segment of the synthetic core starts in the spring of the corresponding year (Table 2), ions that could have been relocated from the summer layer above are not present in the new core segment due to its different origin (Table 2).

2.4 Calculation of the meltwater

In order to quantify the meltwater produced at Lomonosovfonna, two independent approaches were used: a simple positive degree day (PDD) model using instrumental temperature data from stations near Lomonosovfonna; and a coupled snow-energy balance model (van Pelt et al., 2012) that delivers snowmelt as output.

2.4.1 PDD model

We considered temperature instrumental data from three different sites in Svalbard: Longyearbyen Airport, Sveagruva and Ny-Ålesund (data from the Norwegian Meteorological Institute, http://eklima.met.no/). To estimate the number of positive degree days (PDD) at Lomonosovfonna, a lapse rate of $-0.0044$ °C m$^{-1}$ was used (Pohjola et al., 2002). An annual average number of 37 PDD at Lomonosovfonna was calculated when using the combined temperature records of Longyearbyen Airport, Sveagruva and Ny-Ålesund (i.e. average value
of daily temperatures from the three stations), during the period between 1989–2010. The meltwater production was calculated as described by Pohjola et al. (2002), using the melt capacity of snow as a function of the PDD at Lomonosovfonna, considering the degree day factor (DDF) as 3.0 mm water °C⁻¹ d⁻¹ found at Svalbard after calibration against stake measurements (Nuth et al., 2012). In a recent study by Claremar (2013) that employs Polar Weather Research and Forecast model (Polar WRF) (Skamarock et al., 2008; Wilson et al., 2011) modelled temperatures, a value for DDF of 25 mm °C⁻¹ d⁻¹ of water was found at Lomonosovfonna. However, this DDF value has proven to be too high due to the poor modelling of the net mass balance at Lomonosovfonna when using polar–Polar_WRF temperatures and snow accumulation rates for the last decades (Claremar, 2013). Consequently, to calculate the meltwater we employed the DDF value proposed by Nuth et al. (2012) which is more realistic for Lomonosovfonna.

2.4.2 Coupled snow-energy balance model

The coupled model was developed to simulate the surface energy balance and subsurface conditions, in order to predict melt, refreezing and runoff at Nordenskiöldbreen, Svalbard and it is described by van Pelt et al. (2012) and (2014). The meltwater refreezing output of the grid point located at 1200 m a.s.l. was used in this study to account for melting at the Lomonosovfonna ice core site. At this elevation runoff does not occur; which implies that all the available water at the surface (from melt and rain) refreezes within the snow/firn pack.

3 Results and discussion

3.1 Dating of the ice cores

The LF-97 ice core has been dated by different methods (e.g. radioactive horizons, δ¹⁸O-H₂O cycles counting, volcanic horizons) having a time scale that covers the past 800 years (Isaksson et al., 2001; Pohjola et al., 2002). An updated time scale for this ice core has been recently published by Divine et al. (2011).

During the 2009 drilling campaign at Lomonosovfonna, two parallel ice cores were drilled: the LF-09 (36 m deep, this study) and a longer core LF-09_deep (149.5 m deep) (Wendl et al., 2015). Tritium (³H) measurements done in the LF-09_deep ice core estimate the 1963 ³H horizon (Pinglot et al., 1999) at 23.6 m w.e., with a resulting accumulation rate of 0.51 m y⁻¹ w.e. between the ³H radioactive horizon and the top of the ice core (Wendl et al., 2015). In addition, the high resolution chemical data available for the LF-09 ice core (samples
taken each 8 cm) allowed the use of a multilinear regression method (MLR) developed by Moore et al. (2012) to account for volcanic layers in the non-sea salt sulfate concentrations. A detailed description of the usage of the MLR method on the dating of the LF-09 ice core can be found in Vega et al. (2015b). In addition to the MLR method, an automated $\delta^{18}O$-H$_2$O cycles counting routine was used in the dating. This method counted $\delta^{18}O$-H$_2$O annual cycles that had an amplitude $A > 0.1 \%$ ($\delta^{18}O$ uncertainty in the SMOW scale) and a frequency in the sub-annual cycle ($\lambda_{sea}$) larger than 1/3 the accumulation rate (Pohjola et al., 2002). Using both methods, the time scale for the LF-09 core was estimated to span between 1957–2009 (Vega et al., 2015b).

The LF-08 and LF-11 ice cores were dated using the automated $\delta^{18}O$-H$_2$O annual cycles counting routine and by comparing the Cl$^-$ record with the respective LF-09 ice core profile. The LF-08 core data has only been interpreted between the top and 6.4 m due to the presence of an anomalous column of clear ice between 6.4 m and 10.6 m deep which is suspected to be originated by a water-filled crevasse. Clear ice layers of this length have never been observed in any of our ice coring efforts. The summit has a few, but deeply cutting extensional crevasses not visible under the snow cover in the spring. The LF-08 core data has only been interpreted between the top and 6.4 m due to the presence of an anomalous column of clear ice between 6.4 m and 10.6 m deep which is suspected to be originated by a water-filled crevasse. The time scales for the cores were estimated to cover the 1989–2000 and 2004–2011 periods for the LF-08 and LF-11 (Vega et al., 2015a) ice cores, respectively. The time scale of the SP LF-10 snowpit was obtained by assuming a constant snow accumulation rate over the depth-scale, resulting in time coverage between 2009.4–2010.4.

### 3.2 Major ions

All the ionic concentrations were binned to annual averages to obtain equally spaced time series of one year resolution, which can be compared in between the different ice cores. Having all the chemical species as annual averages, their concentrations ($c_i$) were normalized to the mean value for each specie in each ice core record, during the total overlapping period (1957–2009) to compare the variations of the ions in the different ice cores (Equation 1).

$$c_N = \frac{c_i - c_{mean}}{\sigma}, \quad \text{Equation 1}$$
where $c_N$ is the normalized concentration of a given ion, $c_{\text{mean}}$ is the ion mean in the specific ice core or strata, and $\sigma$ is the standard deviation of the series.

When comparing the annual average concentrations between the different ice cores, some of the peaks show a lag between the different records which likely is associated with the uncertainty of the dating of the three different ice cores. We applied a 5-year moving average smoothing to the annual chemical data (Figure 2). The dating error of the LF-08 and LF-09, in respect to the LF-97 ice core, was estimated as $\pm$ 2 years. We found that similar temporal variations experienced by the different ions were registered in the different Lomonosovfonna ice cores during the overlapping period studied (Figure 2).

Table 3 shows the Pearson coefficient (R) values and the Wilcoxon rank sum test between the different species in the LF-97 and LF-09 ice cores, and the LF-08 and LF-09 ice cores, smoothed out with 5-year moving averages of the annual data. The Wilcoxon rank sum test was also applied to the ion series in the LF-08 and LF-09 cores to evaluate the hypothesis that ion concentrations in the different LF-cores are samples from continuous distributions with equal medians. The R-values between the LF-97 and LF-08, LF-08 and LF-09 ice cores were not calculated since the overlapping period using 5-year moving average was too short.

The R-values and the results of the Wilcoxon test in Table 3 suggest that the LF-97 and LF-09 ice-cores, and the LF-08 and LF-09 cores have comparable chemical records for all ions during the period 1956–1996 and 2000–2008, respectively. Consequently, they can be used to interpret the main chemical and climatic patterns at Lomonosovfonna at this resolution. However, the correlation coefficients measured in the LF-08 and LF-09 ice cores are not significant at the 95% confidence interval (with the exception of $\text{Mg}^{2+}$, $R_s = -0.53$).

### 3.3 Ionic distribution in the snowpack

In order to investigate to what degree ions are eluted from the snowpack when meltwater percolates, we first compared the log-transformed concentrations ($\log(c)$) of the different species measured in the LF-09 and LF-11 ice cores at different snowpack faces: i.e. snow, ice, and firn. The chemical record of the LF-09 ice core was considered only during the period 2004–2009 when it overlaps with the LF-11 ice core.

Figure 3 shows that the median $\log(c)$ of ions in the LF-09 ice core is significantly higher, at a 95% confidence level, in the snow compared to ice and firn for $\text{SO}_4^{2-}$, $\text{Cl}$, $\text{NO}_3^-$, $\text{Br}^-$, $\text{Na}^+$ and $\text{K}^+$, with higher $\log(c)$ values also for $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$, however, not...
significant all species. Moreover, concentrations show similar mean–medians in firn and ice. On the other hand, Figure 4 shows that median Log(c) ion concentrations in the LF-11 ice core are significantly higher in the snow compared to both ice and firm only for Br and Mg\(^{2+}\), with SO\(_4\)\(^{2-}\) median in snow being only significantly higher than in ice. Most of the ions, with the exception of NO\(_3^-\) and NH\(_4^+\), show which presents even concentrations in all the strata, while with the exception of NH\(_4^+\) a higher mean–median concentration in ice compared to firm and snow.

Previous work by Pohjola et al. (2002) focused on the effect of periodic melting in the chemical record of an ice core drilled at Lomonosovfonna (LF-97) shows that the average ionic concentrations of the different ionic species were higher in the ice facies than in the firm layers. We observed that this is only significant for Br\(^-\) and NH\(_4^+\) measured in the LF-09 ice core and F\(^-\) and NH\(_4^+\) measured in the LF-11 ice core. Since all ions in the LF-09 and LF-11 ice cores within the period 2004–2011 (10 m deep) are mostly distributed between the snow and firm, we infer that ions in this section of the ice cores have not been heavily relocated by meltwater percolation. Since the amount of meltwater production at the summit of Lomonosovfonna is unknown for the studied years, three different approaches were used in order to estimate and relate it to ionic snowpack redistribution (see section 3.5.).

In order to elucidate the evolution of meltwater production over time, the chemical melt index (\(W_{NaMg}\)), defined as Log(Na\(^+\)/(Mg\(^{2+}\)) (using ionic concentrations in \(\mu\)eq L\(^{-1}\)) (Iizuka et al., 2002; Grinsted et al., 2006) was calculated in the different Lomonosovfonna ice cores (Figure 5 which shows positive melt indices during the last 60 years. As observed in Figure 5, melting at the drilling site is far from being constant; a period of high melt is evident during mid-1980s to mid-1990s which is concomitant with a period of relatively high number of PDDs at Lomonosovfonna. Although the above mentioned method is useful to infer melting regimes at Lomonosovfonna at large time scales (i.e. decadal to centennial), it is not suitable to infer melting at sub- and multi-annual resolutions; therefore, the synthetic ice core approach described in this study presents a suitable option.
3.4 Synthetic ice core

Assuming that snowmelt does not occur during winter, and considering that precipitation records of different Svalbard sites show that most of the precipitation is registered during the winter and autumn seasons (Førland et al., 2011), it is expected that the synthetic ice core (LF-syn) captures the unperturbed chemistry of the winter, autumn, summer-winter and early spring seasons between spring 2007–2010. Figure 6 shows the annual precipitation cycle at Longyearbyen airport and Ny-Ålesund stations and the precipitation amount and snow accumulation from the two stations and the LF-syn core during the period 2007–2011. The snow accumulation in the LF-syn core was calculated as the length (in m w.e.) between two LF-syn core samples which in average represent 1.2 months of accumulation. Both, the meteorological and the ice core records are coherent with each other, depicting higher accumulation rates during the autumn/winter period than spring/summer. Consequently, it is expected that the LF-syn ice core is representative of the snow accumulation regime at Lomonosovfonna during 2007–2010. The flat accumulation observable during the winter 2010 is due to the assumption of a linear time scale when dating each snow layer of the snowpit dug out in 2010 (SP LF-10). In addition, the average annual mass loading of each ion was calculated for the period 1980–2009 by averaging the annual ion loads calculated in the LF-97 and LF-09 cores. This procedure averaged out the possible effects of percolation and relocation of ions between the strata corresponding to different years. This estimate was then compared with the mass loading of the different ions corresponding to individual years in the LF-syn core (i.e. 2007–2010) which are assumed to represent cumulative autumn-winter-early spring snow accumulation unaltered by meltwater percolation or ion relocation. It was found that the 5-year LF-syn record represents between 70–200 % of the 30-year average ion mass loading with NH$_4^+$ and Mg$^{2+}$ located at the bottom and top percentage boundaries, respectively, and NO$_3^-$ and SO$_4^{2-}$ representing 94 % and 111 % of the average, respectively. Keeping in mind that the mass loading for most of the ions show increasing values since 2005 (not shown), thus, influencing the percentage of average mass loading in the LF-syn core, we consider that this synthetic core is adequate to investigate ion relocation during the period 2007–2011. The LF-syn core was then compared with the LF-11 core to evaluate the effects of ion elution/deposition between 2007–2010 (recorded in the LF-11 ice core) compared to the unperturbed LF-syn ice core (Figure 7). Since the top part of the LF-11 core (0–0.6 m w.e.) was not used to construct the LF-syn core (Table 2) to avoid any bias caused for the snow accumulated after the
In spring 2010 and 2011, this period was not considered in the normalization of the LF-11 ionic concentrations. Figure 7 shows that the LF-11 record has noticeable large cN peaks, e.g., around summer 2009, that can be associated with the increase in ionic concentrations by the relocation of ions by the refreezing of percolation water. Figure 8 shows the differences between cN in both ice cores (LF-11 syn – LF-syn) calculated after interpolating the records at 0.01-year time steps to homogenize the data. A lowpass filter (half-year moving average) was used to filter out high frequency processes superimposed to the percolation and relocation effect (Figure 8); consequently, a cutting threshold of half a year was assumed for the relocation of ions. Using the filtered time series shown in Figure 8, we considered a relocation period when the differences in cN are positive. Positive differences indicate higher ionic concentrations in the LF-11 ice core with respect to the LF-syn ice core, therefore, ice-firm layers enhanced in ions due to relocation by percolation water. Negative differences indicate ionic elution happening at that layer. Consequently, the study period was divided in four sub-periods denoted with Roman numbers (Figure 8). It is worth saying, that even though the LF-11 core was used for comparison with the LF-syn core only between 2007.4–2010.4, the effects of melt water produced and percolated during the summer of 2010 are recorded in the LF-11 core. Consequently, Period I encompasses the melting season of the summer-spring months of 2010 (elution period). Period II reflects the deposition period after the spring-summer of 2010. Period III represents elution occurred between summer of 2009 and summer of 2008; and Period IV encompasses a deposition period from spring of 2008 to spring of 2007. We considered a relocation peak when the differences in cN are higher than twice the standard deviation of the normalized concentrations of each ion (dashed red line in Figure 8).

From Figure 8, it can be observed that most of ions such as Cl−, Na+, with the exception of NH4+ and Ca2+ share similar elution/deposition features in Periods I–IV. and present clear deposition/elution cN peaks. On the other hand, SO42− only shows a deposition peak with an elution zone, rather than a single elution peak. This can be interpreted as SO42− eluting steadily and further down the snowpack than the other ions during this period (Figure 8).

We estimate a minimum ionic relocation length as the difference in depth between the minimum/maximum (elution/deposition) maximum/minimum (deposition/elution) cN peaks observed in Periods I–II (Figure 8, Table 4). The difference was not calculated in Periods III–IV since the time series are truncated before reaching a maximum value, however the elution minima are noted in Table 4, as shown in Figure 8 and presented in Table 4. The relocation
length was calculated for all ions, with the exception of $\text{SO}_4^{2-}$, $\text{NH}_4^+$, and $\text{Ca}^{2+}$, which does not show an elution peak that is significant within the time window studied. For the ions that show more than one significant deposition/elution peak, the relocation length calculated considering the second maximum/minimum $c_N$ peak is also shown in Table 4. Considering the deposition/elution/deposition $c_N$ peaks estimated above, the partial ionic elution scheme at Lomonosovfonna for the last 5 years period 2007–2010 can be inferred, with $\text{SO}_4^{2-}$ being the most mobile ion and $\text{NO}_3^-$ being the most mobile the least mobile one. This partial elution scheme agrees with previous studies done at Lomonosovfonna (Moore and Grinsted, 2009) mainly in which found that locating $\text{NO}_3^-$ at the end of the was highly mobile elution sequence. However, it should be noticed that we estimated two possible relocation lengths based in the depth difference between deposition/elution peaks (as explained before). Therefore, considering a $\text{NO}_3^-$ relocation length of 1.16 m, the elution sequence agrees with previous findings by Moore and Grinsted (2009), locating the acidic ions (SO$_4^{2-}$ and NO$_3^-$) as more mobile than the other ions. The partial elution sequence and ion relocation lengths shown in Table 4 suggest that the less mobile ions are relocated by the meltwater at short lengths, probably trapped in thin and medium-thick ice layers present within the ice column observable in the LF-97, LF-09 and LF-11 cores (Figure 9), or in refrozen water that soaks the firn column filling the pore space. Nevertheless, the results shown in Figure 8 and Table 4 are not absolute for the full length of the Lomonosovfonna core but rather the case for years with apparently moderate melting (e.g., MP<50%). In years were summers are warmer and/or longer, More mobile ions may percolate further down in the snowpack and get trapped in medium-thick to thick ice layers which start to form at about 3–10 m deep in the ice column as observable in the LF-97 and LF-09 cores (Figure 9). In order to estimate how the ionic relocation length during 2007–2010 is connected to meltwater percolation length and snowpack melting, we have estimated the melt percentage at Lomonosovfonna using two different methods, as shown in the following section.

3.5 Meltwater production at Lomonosovfonna

The produced meltwater obtained by using the PDD and snow-energy model approaches are shown in Figure 10 for the period 1979–2012 (calculated using PDD and instrumental temperatures), and 1989–2010 (using the snow-energy model). The production of meltwater at the summit of Lomonosovfonna has increased at a rate of +0.0011 m yr$^{-1}$ w.e.
toward the last decades (corresponding to the linear trend of meltwater production calculated with the PDD and instrumental temperatures approach, Figure 10). The meltwater production shows a minimum around 1995, which is present when using both approaches (Figure 10). The average melting between 1989–2010 was calculated as 0.17 m w.e. when using the PDD and instrumental temperature approach. When considering the period between 2007–2010 (Figure 11), the melting shows alternating warm and cold years (2007/2009, and 2008/2010, respectively), with meltwater average values of 0.19 m w.e. and 0.27 m w.e. when using the instrumental temperatures, and the coupled snow-energy model, respectively. Alternatively, meltwater production was also calculated by using modelled temperatures obtained with the Polar WRF model at the summit of Lomonosovfonna and a DDF of 3.0 mm water °C d⁻¹. An average meltwater production of 0.07 m w.e. and 0.05 m w.e. were obtained for the periods 1989–2010 and 2007–2010, respectively when using the Polar WRF modelled temperatures. The meltwater production obtained by the Polar WRF approach gives values that are significantly lower than the meltwater obtained by using both the PDD and snow-energy model approaches which is a consequence of the less number of PDDs per year estimated at the summit of Lomonosovfonna when using the Polar WRF model (i.e. 18 PDDs per year between 1989–2010) explained by the fact that the Polar WRF model produces lower surface temperatures compared to the lapse-rate based temperatures at this site. Therefore, the meltwater calculated by using Polar WRF modelled temperatures were not considered in this study.

In order to estimate the impact of melting on the snowpack ionic content at the summit of Lomonosovfonna, the percentages of the annual snow accumulation that melts (Table 5) were calculated using the results in Figure 10 and Figure 11 and the annual accumulation rate between 2007–2010 at Lomonosovfonna obtained from the LF-09 and LF-11 cores. The melt percentage (MP) obtained by using the instrumental temperatures (48% for the period 2007–2010) was in the order of previously reported values of 47% of melt during the warmest years and 28% during the coldest, during the period 1976–1995 (Pohjola et al., 2002). The relatively high MP values obtained in this study for the period 2007–2010 can be explained by the increase in temperatures at the site with a consequent steady increase of the number of PDD at the summit of Lomonosovfonna at a rate of 0.4 d y⁻¹ for the period 1979–2012 in which instrumental temperatures exist in all the three stations used, Sveagruva, Ny-Ålesund and Longyearbyen airport; the MPs calculated using the PDD approach over the period 1979–2010 show a steady increase of 1% y⁻¹ in line with the trend in
decreasing the annual snow accumulation in $-0.01 \text{ m yr}^{-1}$ w.e. during the same period (accumulation data from the LF-09 ice core).

However, the calculated MPs using the PDD approach and the snow-energy do not agree with the results obtained by the synthetic core approach which suggest that moderate melting during the 2007–2010 period has not been high (i.e. < 50 %) which is also supported by the stratigraphy observed in the LF-09 and LF-11 cores (Figure 9).

Due to the dissimilar results of MP obtained using the PDD and snow-energy model approaches (Table 5), we compared the density profiles of the shallow ice cores used in this study (LF-08, LF-09 and LF-11) with the total layer density values obtained using a simple firn-densification model (Reeh et al., 2005). The ice core density profiles were binned in annual averages in order to be comparable with the output of the firn-densification model.

As described by Reeh et al. (2005), the model requires both annual average temperatures and snow accumulation at the study site as input, which were set as $-18.3 \degree \text{C}$ and 0.39 m w.e., according to instrumental temperatures from Sveagruva, Svalbard Airport and Ny-Ålesund (the lapse rate employed to calculate the temperatures at the Lomonosovfonna summit was $-0.0044 \degree \text{C m}^{-1}$), and average accumulation rates obtained from the LF-09 and LF-11 ice cores, respectively, for the period between 2007–2010. The firn-densification model also requires the surface snow density, which was set as 350 kg m$^{-3}$, and a defined spatial resolution, set as 0.5 m. The firn-densification model considers the percentage of melting as one of the input variables, showing output density values versus depth. Output densities of 900 kg m$^{-3}$ are expected when the percentage of melt reaches 100 %.

Four different melt scenarios where considered: MP equal to a) 20 %, b) 30 %, c) 45 %, and d) 70 %. The results of the comparison between the real ice core density profiles and the output of the firn-densification model are shown in Figure 12.

According to Figure 12, the firn-densification model shows better agreement with the measured density profiles in the top 10 m when the MP was set between 20 % and 30 %.

This agrees with the physical melt index of the LF-09 ice core (22 %), calculated as the percentage of clear ice present in the ice core (considering the ice core length in m w.e.).

However, the agreement between the firn-densification model and the density profiles is poor for depths deeper than 10 m (Figure 12 a–b) considering this range or MP. Figure 12 c–d, show the comparison between the firn-densification model and the density profiles using a MP of 45 % and 70 %. The agreement between the model and the
measurements is better through the whole depth profile when setting the MP to 45% (Figure 12c). This agrees with the physical melt index of the LF-97 ice core (50%), calculated between 1957 and 1997, however, it is not consistent with the physical melt index of the LF-09 ice core (25%), calculated for the same period.

Considering the results shown in Table 5 and the firm-densification model output shown in Figure 12a–d, it is plausible to think that the MP at Lomonosovfonna is not straightforward to estimate either using a simple PDD or the snow-energy model approach. Moreover, the use of Polar WRF temperatures at Lomonosovfonna as input to obtain the MP at the site is ruled out since it predicts MP values considerably lower than the values suggested by the density profiles both measured and modelled (i.e. an average MP of 12% for the period 2007–2010 when Polar WRF modelled temperatures and a DDF of 3.0 mm water °C d⁻¹ are used to calculate the meltwater production). It also needs to be considered that the firm-densification model assumes a constant melt index during the ice core time span. Therefore, the firm-densification model does not include the variability in meltwater production at Lomonosovfonna through time which is key to the understanding of ion relocation within the snowpack at long time scales; however, the MP estimated here are suitable to understand the ionic relocation and water percolation during the period 2007–2010.

Figure 13 shows a comparison between the LF-11 and the LF-syn ice core depth–time scale. It is clear from Figure 13 that the depth differences between the ice cores (black and grey lines) can be related to a partial melting of the snowpack and refreezing of the meltwater taking place between the 2007–2011 period, as evidenced by the ionic relocation. An estimate of the decrease in depth of the LF-syn ice core by the effects of snowpack melting considering a MP = 20, 30, 48 and 70% during 2007–2010 as suggested by the firm-densification model, MPs obtained using the PDD approach (using instrumental temperatures) and the snow-energy model is shown in Figure 13. It can be observed that a MP = 20–30% results in a LF-syn ice core depth-time scale highly similar to the depth-time scale of the LF-11 ice core during the 2007–2010 period, confirming that the MP during that period is coherent with the results of the firm-densification model but not with the PDD results shown in Table 5. This relatively low MP reinforces the hypothesis that during this period, ion relocation took place at shallow moderate depths (0.5–2 m) and that the meltwater percolation depth was most probably in the same order, with refreezing of
meltwater within the snowpack pore space or by forming thin ice layers (0.03–0.15 m) 
(Figure 9).

4 Conclusions

By comparing different ice cores from Lomonosovfonna and using a synthetic ice core 
approach, we have been able to estimate the elution signal and relocation length of different 
ions measured at the study site, in order to assess the transfer function between the 
atmospheric ionic concentrations and the concentration in snow and ice.

Our results show good agreement between the ionic records of three different ice cores drilled 
during different years, using normalized concentrations and five year moving averages. 
Therefore, we reiterate that the different ice core records from Lomonosovfonna all share the 
same climatic and chemical features, despite the fact that cores have been retrieved in 
different years, were sampled at different resolutions, and were analyzed at different 
laboratories. Our conclusion is that summer melting does not degrade the climatic signals.

By using the synthetic ice core approach, we could estimate a partial elution sequence for the 
summit of Lomonosovfonna, as $\text{SO}_4^{2-} > \text{NO}_3^- > \text{SO}_4^{2-} > \text{NH}_4^+ > \text{Mg}^{2+} > \text{Cl}^-, \text{K}^+ > \text{Na}^+, \text{Ca}^{2+}$—which agrees with previous reports. This elution sequence points towards the acidic ions 
as being the most mobile within the Lomonosovfonna snowpack. Considering the differences 
between the LF-11 and the LF-syn ice cores, we conclude that the relocation length of most 
the ions during the 2007–2009 period is in the order of 1 m, therefore, the ions are eluted 
and re-deposited within the annual snow layer, considering present average accumulation rate 
at Lomonosovfonna (i.e. < 1 m of snow per year). According to our results, only $\text{SO}_4^{2-}$ shows 
percolation lengths that could potentially reach deeper than the previous year of snow 
accumulation (>2 m), which affects the annual atmospheric signal and prevents any high 
resolution (seasonal, annual) analysis to be possible in Lomonosovfonna ice cores. However, 
as we have concluded before Consequently, using 5-year moving averages of the ionic data 
allows having comparable records when different ice cores are used.

By using the PDD and the snow-energy model approaches to estimate the percentage of melt 
(MP) at Lomonosovfonna, we have estimated average annual MP in the range of 48% to 70% 
for the period between 2007–2010, in contrast to the moderate lesser melting suggested by the 
LF-syn core for the same period. In order to constrain the MP, we have compared different 
density profiles obtained at the Lomonosovfonna drilling sites with a simple firn-densification
model, obtaining a most probable average annual MP of 30% for the 2007–2010 period which is consistent with the results of the synthetic ice core approach, and 45% of melt for the last 60 years. The lower melting percentages inferred for the 2007–2010 period compared with the whole period covered by the LF.-09 core are most probably a result of a combination of relatively high snow accumulation rates and reduced PDD during the 2007–2010 period despite of the warmer conditions registered during the last decades.

Considering our findings, we conclude that despite of the warmer conditions and higher number of PDD registered at Lomonosovfonna during the last decades, the ionic signal affected by melting is retained within the same year of deposition for all major ions, with the exception of SO$_4^{2-}$ which can possibly be re-deposited in previous annual layers.

Acknowledgements

The authors want to thank the Lomonosovfonna 1997, 2008 and 2009 drilling teams and NPI field logistics for their support, C. Zdanowicz and G. Engström, Uppsala University, J. Moore, Arctic Centre, J. Zábori, Stockholm University, and S. Bejai, SLU for their comments and sharing of analytical lab facilities. This work was supported within the Marie Curie Initial Training Network NSINK ITN-2007.1.1, ENV., 215503 with complementary economic support by Ymer-80, the Arctic Fieldwork Grant by the Svalbard Science Forum, Uppsala Geographical Association, Sweden, and to the EU Regional Development Foundation, project 3.2.0801.12-0044.
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### Table 1: Drilling site and ice core description for the three different cores used in this study.

<table>
<thead>
<tr>
<th>Ice core</th>
<th>Drilling date</th>
<th>Location</th>
<th>Elevation (m a.s.l.)</th>
<th>Length (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF-97</td>
<td>May 1997</td>
<td>78° 51’ N 17° 25’ E</td>
<td>1250</td>
<td>121.6</td>
<td>Isaksson et al. (2001)</td>
</tr>
<tr>
<td>LF-09</td>
<td>Mar. 2009</td>
<td>78° 49’ N 17° 25’ E</td>
<td>1200</td>
<td>36.0</td>
<td>Vega et al. (2015b)</td>
</tr>
<tr>
<td>SP LF-10</td>
<td>Mar. 2010</td>
<td>78° 49’ N 17° 25’ E</td>
<td>1200</td>
<td>1.5</td>
<td>This work</td>
</tr>
<tr>
<td>LF-11</td>
<td>Apr. 2011</td>
<td>78° 49’ N 17° 25’ E</td>
<td>1200</td>
<td>7.6</td>
<td>Vega et al. (2015a)</td>
</tr>
</tbody>
</table>
Table 2 Synthetic ice core construction using the different Lomonosovfonna shallow cores (LF-08 and LF-09) and SP LF-10 snowpit. "The top meter of the LF-11 was not used to construct the synthetic ice core but it is shown here as reference to account for the final depth of the synthetic core.

<table>
<thead>
<tr>
<th>Ice core</th>
<th>Depth interval (m w.e.)</th>
<th>Time interval (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF-11</td>
<td>0.0–0.6</td>
<td>2011.4–2010.4</td>
</tr>
<tr>
<td>SP LF-10</td>
<td>0.6–1.4</td>
<td>2010.4–2009.3</td>
</tr>
<tr>
<td>LF-09</td>
<td>1.4–1.8</td>
<td>2009.3–2008.3</td>
</tr>
<tr>
<td>LF-08</td>
<td>1.8–2.3</td>
<td>2008.3–2007.4</td>
</tr>
</tbody>
</table>
Table 3 Top table: Pearson coefficients ($R$) at a 95% confidence interval and t-test Wilcoxon rank sum test results ($p$-values), at a 95% confidence interval, between the different ions measured in the LF-97 and LF-09 ice cores (top table) (normalized concentrations and smoothed out as 5-year running averages). The overlapping period is 1957–1996 (top table). $p$-values of the Pearson correlation have been corrected for the reduced degrees of freedom introduced by the 5-year smoothing. Significant values (correlation, $p < 0.05$; t-test Wilcoxon rank sum test $p > 0.05$) are shown in italics. Bottom Table: Wilcoxon rank sum test at a 95% confidence interval between the different ions measured in the LF-08 and LF-09 ice cores (normalized concentrations and smoothed out as 5-year running averages). The overlapping period is 2000–2008. $N$ represents the sample size. Significant values ($p < 0.05$) are shown in italics. The overlapping period is 1957–1997 (top table) and 1989–2008 (bottom table).

<table>
<thead>
<tr>
<th>Ion</th>
<th>Cl$^-$</th>
<th>NO$^-$</th>
<th>SO$_4^{2-}$</th>
<th>Na$^+$</th>
<th>NH$_4^+$</th>
<th>K$^+$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF-97 and LF-09 ice cores</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R (N=36)</td>
<td>0.46</td>
<td>0.64</td>
<td>0.56</td>
<td>0.49</td>
<td>0.77</td>
<td>0.66</td>
<td>0.36</td>
<td>0.72</td>
</tr>
<tr>
<td>Wilcoxon rank sum test ($p$-value, $N=36$)</td>
<td>0.32013</td>
<td>0.04013</td>
<td>0.13035</td>
<td>0.04016</td>
<td>0.04015</td>
<td>0.39061</td>
<td>0.46100</td>
<td>0.06034</td>
</tr>
<tr>
<td>LF-08 and LF-09 ice cores</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R (Wilcoxon rank sum test ($p$-value, $N=5$))</td>
<td>0.24084</td>
<td>0.02010</td>
<td>0.22</td>
<td>0.30055</td>
<td>0.32002</td>
<td>0.16069</td>
<td>0.23100</td>
<td>0.52017</td>
</tr>
</tbody>
</table>
Table 4 Minimum relocation length estimated for each ion measured in the LF-11 ice core. Secondary relocation peaks are also depicted.

<table>
<thead>
<tr>
<th>Ion</th>
<th>SO$_2^-$</th>
<th>Mg$^{2+}$</th>
<th>Cl$^-$</th>
<th>K$^+$</th>
<th>Na$^+$</th>
<th>NO$_3^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periods I–II: Relocation length (m)</td>
<td>1.205</td>
<td>1.091</td>
<td>1.09</td>
<td>0.791</td>
<td>1.2066</td>
<td></td>
</tr>
</tbody>
</table>

Secondary peak (m) | 1.16 | 1.16 | 1.16 |
Secondary peak (year) | 2007.4 | 2007.4 | 2008.9 |
Table 5 Percentages of melted annual snow accumulation (MP) calculated with the PDD approach (Pohjola et al., 2002; Nuth et al., 2012) using instrumental temperatures, and the snow-energy model (van Pelt et al., 2012).

<table>
<thead>
<tr>
<th>Year</th>
<th>Instrumental temperatures</th>
<th>Snow-energy model</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>34</td>
<td>52</td>
</tr>
<tr>
<td>2009</td>
<td>55</td>
<td>81</td>
</tr>
<tr>
<td>2008</td>
<td>34</td>
<td>68</td>
</tr>
<tr>
<td>2007</td>
<td>69</td>
<td>78</td>
</tr>
<tr>
<td>Average</td>
<td>48</td>
<td>70</td>
</tr>
</tbody>
</table>
Figure 1. Map of Svalbard showing the main settlements: Longyearbyen, Ny-Ålesund and Pyramiden, and the LF-97, LF-08, LF-09 and LF-11 drilling sites at Lomonosovfonna.
Figure 2 Comparison of normalized ionic concentrations ($c_N$) in the different LF-ice cores using a 5-year moving average.
Figure 3. Box plot of log-transformed ionic concentrations (Log(c)) found in the different stratigraphic units in the LF-09 ice core between 2004 and 2009. $n$ represents the sample size in each stratigraphic unit, and whiskers are Tukey style.
Figure 4. Box plot of ionic concentrations (Log(c)) found in the different stratigraphic units in the LF-11 ice core between 2004 and 2011. \( n \) represents the sample size in each stratigraphic unit, and whiskers are Tukey style.
Figure 5. Melt index $W_{NaMg}$ calculated in the different Lomonosovfonna ice cores. The values correspond to 5-year moving averages. The dashed rectangle lines indicates a high melting period during mid-80s to mid-90s.
Figure 6. Annual precipitation cycle at Longyearbyen airport and Ny-Ålesund for the period 2007–2011 (left) and monthly precipitation amount at the stations and snow accumulation at Lomonosovfonna given by the LF-syn core (right).
Figure 7. Comparison between a *synthetic* ice core (LF-syn, black) and the LF-11 ice core (grey). Ionic concentrations are normalized ($c_N$) to mean values according to the LF-syn ice core time scale.
Figure 8.8. Difference between the normalized ionic concentrations ($c_N$) in the LF-11 and the LF-syn ice cores (black line). Twice the standard deviation (dashed red line) and zero values (horizontal dashed black line) are also shown. Deposition is a positive excursion and elution zones are negative excursions from the mean in each diagram. A lowpass filter (half-year moving average) is shown in red. Different periods of deposition and elution have been noted with roman numbers.
Figure 9. Number of ice layers found at different depths in the: LF-97 (left), LF-09 (centre) and LF-11 (right) ice cores. The ice layers were divided in three classes according to their thickness: thin layers (*), medium-thick layers (△) and thick layers (●).
Figure 10.14: Produced meltwater calculated at Lomonosovfonna using the PDD (black) and snow-energy model (dashed red) approaches. The linear trend of meltwater calculated with the PDD approach and instrumental temperatures is also shown over the 1979–2012 period (grey).
Figure 11. Meltwater calculated at Lomonosovfonna during the period 2007–2010 using the different approaches: PDD and instrumental temperatures (black); and the snow-energy model (dashed red). The percentages above each line represent the average melt percentage (MP) during the studied period, estimated by the different approaches.
Figure 12. Comparison between the LF-08, LF-09 and LF-11 ice core density profiles (annual averages) and the output of the firn-densification model (Reeh et al. 2005), considering: a) 20% of melt, b) 30% of melt, c) 45% of melt, and d) 70% of melt.
Figure 13: Depth–time scales for the LF-11 and LF-syn ice cores during 2007–2011 (black and grey lines, respectively). Blue dashed, black-dot-dashed, green and red lines represent the synthetic core depth–time scale considering a MP of 20%, 30%, 48% and 70%, respectively.