Pre-melt-season sediment plume variability at Jökulsárlón, Iceland, a preliminary evaluation using in-situ spectroradiometry and satellite imagery

How to cite:

© 2016 The Authors

Version: [not recorded]

Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.1017/aog.2016.20

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data policy on reuse of materials please consult the policies page.

oro.open.ac.uk
Pre-melt-season sediment plume variability at Jökulsárlón, Iceland, a preliminary evaluation using in-situ spectroradiometry and satellite imagery

How to cite:

© 2016 The Authors

Version: Version of Record

Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.1017/aog.2016.20

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online’s data policy on reuse of materials please consult the policies page.
Pre-melt-season sediment plume variability at Jökulsárlón, Iceland, a preliminary evaluation using in-situ spectroradiometry and satellite imagery

Richard HODGKINS,1 Robert BRYANT,2 Eleanor DARLINGTON,1 Mark BRANDON3

1Department of Geography, Loughborough University, Leicestshire LE11 3TU, UK
E-mail: r.hodgkins@lboro.ac.uk
2Department of Geography, University of Sheffield, Sheffield S10 2TN, UK
3Department of Environment, Earth & Ecosystems, Open University, Walton Hall, Milton Keynes MK7 6AA, UK

ABSTRACT. High-latitude atmospheric warming is impacting freshwater cycling, requiring techniques for monitoring the hydrology of sparsely-gauged regions. The submarine runoff of tidewater glaciers presents a particular challenge. We evaluate the utility of Moderate Resolution Imaging Spectroradiometer (MODIS) imagery for monitoring turbid meltwater plume variability in the glacier lagoon Jökulsárlón, Iceland, for a short interval before the onset of the main melt season. Total Suspended Solids concentrations (TSS) of surface waters are related to remotely-sensed reflectance via empirical calibration between in-situ-sampled TSS and reflectance in a MODIS band 1-equivalent wavelength window. This study differs from previous ones in its application to an overturning tidewater glacier plume, rather than one derived from river runoff. The linear calibration improves on previous studies by facilitating a wider range of plume metrics than areal extent, notably pixel-by-pixel TSS values. Increasing values of minimum plume TSS over the study interval credibly represent rising overall turbidity in the lagoon as melting accumulates. Plume extent responds principally to consistently-strong offshore winds. Further work is required to determine the temporal persistence of the calibration, but remote plume observation holds promise for monitoring hydrological outputs from ungauged or ungaugeable systems.

KEYWORDS: atmosphere/ice/ocean interactions, fluvial transport, glacier hydrology, ice/ocean interactions, tidewater

INTRODUCTION

One of the most important ways in which Arctic hydrology is responding to rapid atmospheric warming is by changing the timing and magnitude of freshwater runoff to the marine environment, with potentially profound implications for coastal circulation, fluxes of sediment and nutrients to near-shore ecosystems and zooplankton productivity (Statham and others, 2008; Arendt and others, 2011). Within the high-latitude hydrologic cycle, glaciers play an important role in modulating river flow and in the delivery of sediments and solutes to lowlands and coasts. Atmospheric warming is driving increased runoff through enhanced rates of melting and through the lengthening of melt seasons, which is reflected in both widespread glacier retreat and augmented river flows. Globally, the stability of glaciers and ice sheets with marine margins is expected to be one of the most important factors contributing to 21st-century sea-level rise (Church and others, 2013). However, understanding of the hydrology of marine-terminating or tidewater glaciers lags behind that of their terrestrial counterparts (Joughin and others, 2012).

An abiding, fundamental problem is that runoff from tidewater glaciers emerges in an inaccessible, submarine location and therefore cannot be measured or monitored directly (Straneo and others, 2013). Yet this runoff is fresh, buoyant and often turbid; hence, it frequently forms observable, overturning plumes (Chu, 2013). These plumes are typically much wider than many river channels, and so more amenable to observation with remotely-sensed imagery. Their characteristics can therefore be measured and their variations tracked, which is of benefit for the study of both the large-scale hydrology of remote, ungauged (and ungaugeable) regions, and the stability and dynamics of large glaciers draining ice sheets.

Remote estuarine and coastal plume monitoring is already well established for non-glacial environments (e.g. Curran and Novo, 1988; Doxaran and others, 2002; Hu and others, 2004; Miller and McKee, 2004) but has only of late been applied to glacial ones (e.g. Chu and others, 2009, 2012; McGrath and others, 2010; Tedstone and Arnold, 2012; Hudson and others, 2014). These latter studies, while demonstrating the potential for plume monitoring in Arctic fjord environments, have had a focus on melt-season, river-fed plumes (which enter a fjord at its surface, rather than at its base), mostly located in West Greenland. Plume monitoring therefore requires validation in a range of environments and in different seasons. In particular, remote studies of specific tidewater glacier plumes are almost entirely absent. Yet plumes, being the only visible expression of tidewater glacier runoff, constitute a link between ice-sheet hydrology and oceans that can be investigated remotely (Chu and others, 2012).

Consequently, the aim of this work is to evaluate the utility of frequent-repeat Moderate Resolution Imaging Spectroradiometer (MODIS) imagery for detecting and monitoring variation in plumes, as indicated by the Total Suspended Solids concentration (TSS) of surface waters, in the accessible glacier lagoon Jökulsárlón, Iceland. In-situ spectral reflectance and TSS measurements were made before the onset of the main melt season in April 2012. Correlation of reflectance and...
TSS at all wavelengths is used to identify the most appropriate band of the MODIS instruments on board NASA’s Terra/Aqua satellites (http://modis.gsfc.nasa.gov/), for mapping TSS. Plume variability from mid-April to the end of May 2012 is then identified and discussed in terms of the hydrologic development of Jökulsárlón.

CHARACTERISTICS OF JÖKULSÁRLÓN

Iceland is a high-latitude environment, where glaciers play an important role in hydrology, feeding major rivers and supplying more than 30% of total runoff (Björnsson and Pálsson, 2008). A general glacier recession since the end of the 19th century has accelerated in the last decade, such that the main ice caps are likely to lose up to 35% of their present volume by the middle of the 21st century (Jóhannesson and others, 2006; Bergström and others, 2007). Meltwater-main ice caps are likely to lose up to 35% of their present volume by the middle of the 21st century (Jóhannesson and others, 2006; Bergström and others, 2007). Meltwater-derived runoff is projected to peak around the same time, before returning to present-day values around the end of this century (Jóhannesson and others, 2007).

Jökulsárlón itself (Fig. 1) is a 23 km² (2012) tidal lagoon in southeast Iceland, formed in the 1930s as the Breiðamerkurjökull outlet glacier of the Vatnajökull ice cap retreated from an overdeepening (Björnsson and others, 2001). Breiðamerkurjökull calves ~0.3 km² of ice into Jökulsárlón per year, and as the glacier retreats, the lagoon continues to grow, at a rate of up to 0.5 km² a⁻¹. Further growth of Jökulsárlón is probable, as the glacier bed is below sea level for ~20 km upstream of its current terminus (Björnsson and others, 2001). Runoff from Breiðamerkurjökull directly enters Jökulsárlón, such that the deposition of glacial sediment within the lagoon has reduced deposition offshore, accelerating coastal erosion, which proceeded at a rate of 8.5 m a⁻¹ for much of the 20th century in the vicinity of Iceland’s main road (Vikingsson, 1991; Jóhannesson, 1994).

DATA SOURCES AND METHODS

The TSS of surface waters in Jökulsárlón is here related to remotely-sensed surface reflectance via a simple, single-band, in-situ calibration. The lagoon was accessed by Zodiac boat over 20–22 April 2012; simultaneous surface-water samples and reflectance measurements (Fig. 1) were obtained on each of these 3 d. In total 15 mL × 500 mL surface-water samples were acquired, filtered through 0.45 µm cellulose-nitrate membranes and the total mass of suspended material determined gravimetrically. Surface reflectance was measured with an Analytical Spectral Devices (ASD) Inc. HandHeld 2 spectroradiometer, using a 25° foreoptic. Prior to each measurement, reflectance spectra from a calibrated Spectralon tablet were collected, so that raw Digital Number measurements could be post-processed to absolute reflectances. At each location 5–12 (on average 8) near-nadir spectral measurements were made between 12:05 and 14:29 local time, and averaged to reduce the effects of variable sky and surface conditions.

Cloud-free imagery was initially identified from the NASA Rapid Response MODIS mosaic of the Arctic (http://lance.modis.eosdis.nasa.gov/imagery/subsets?mosaic=Arctic), following which MOD09GQ (Terra) and MYD09GQ (Aqua) daily 250 m-resolution images were downloaded from the Reverb|ECHO service of NASA’s Earth Observing System Data and Information System (EOSDIS; http://reverb.echo.nasa.gov/reverb). This level-2 imagery has been corrected for gases, aerosols and thin cirrus clouds (Vermote and Vermeulen, 1999). The images used were acquired between 11:56 and 13:55 local time (Table 1), giving near-nadir views with suitable solar illumination. The absence of cloud over Jökulsárlón itself was confirmed using the internal cloud algorithm flag of the ‘state_1 km_1’ QA layer in the imagery, which was processed in its native sinusoidal projection.

In order to obtain an up-to-date lagoon outline, a clear-sky Landsat 7 SLC-off scene (30 m-resolution) from 28 May 2012 was reprojected to the MODIS sinusoidal system (Fig. 1). The scene was gap-filled using the Focal Analysis tool within Erdas Imagine on a layer stack composed of all the band files except the thermal and panchromatic (http://landsat.usgs.gov/ERDAS_Approach.php). Jökulsárlón was digitized from the resulting scene to obtain an Area of Interest (AOI) file, which could be used to subset MODIS images. To account for the lower spatial resolution of MODIS compared with Landsat, the AOI file was overlaid on a MODIS image and edited to remove mixed land/water pixels, leaving only water pixels. This also removes the potential for spurious high reflectances from coarser MODIS pixels at the lagoon edge containing both land and water. The final AOI file was used to subset appropriate MODIS images to the Jökulsárlón water surface.

In order to evaluate the effects of environmental conditions on plume characteristics, the following, further datasets were acquired. Time series of tidal heights for Hornafjörður (64°9.000′N, 15°7.200′W), 48 km northeast of Jökulsárlón on Iceland’s southern coast, were obtained from the www.Tide and Current Predictor (http://tbone.biol.sc.edu/tide/, using Xtide 2 software, http://www.flaterco.com/). Tidal tendency (Δtide, positive for flood and negative for ebb tides) was then calculated for the time of image acquisition. Coastal weather data (hourly air temperature, T, and precipitation, P) for the Kvísker weather station (WMO number 4886, 63° 57.576′N, 16° 5.465′W, 30 m a.s.l.) 13 km southwest of Jökulsárlón, were supplied by Veðurstofa Islands. Because of the highly localized nature of wind regimes, wind velocity (Vw) and direction data were obtained from a University of Iceland Automatic Weather Station located...
on Breiðamerkurjökull itself (64°11.757′N, 16°22.123′W, 570 m a.s.l.)

RESULTS AND ANALYSIS

The TSS of surface-water samples ranged from 0.17 to 0.58 g L\(^{-1}\) (Table 1). The corresponding reflectance varies with wavelength, although there is a consistent response (reflectance increasing with TSS) in a window that corresponds to MODIS band 1 (B1, 620–670 nm; Fig. 2a). TSS and reflectance are well correlated (\(r = 0.86\)) in this wavelength window: here the correlation plateau is very broad and clear (Fig. 2b), suggesting little benefit from further examination of derivative spectra. The strong correlation between in-situ-sampled TSS and 620–670 nm reflectance gives confidence that the B1 reflectance can be calibrated to values of TSS, using the relationship

\[
TSS = 4.7004\text{ref}
\]

\((R^2 = 0.74, \ p = 0.00)\) where ref is reflectance in B1 or the 620–670 nm wavelength window (Fig. 2c; Chen and others, 2015). This simple calibration has the benefit of being linear for the range of TSS sampled in April 2012, with no indication of the reflectance saturation observed in some comparable studies, for example, Chu and others (2009), who also measured higher reflectances for a given TSS (presumably a function of lithology and/or particle-size distribution).

The days of in-situ sampling were consistently overcast, so in-situ reflectances cannot be compared with MODIS reflectances directly. But using the calibration, it is possible to map TSS variability in the lagoon for cloud-free days. Allowance needs to be made for the presence of floating ice, mainly in the form of icebergs calved from the terminus of Breiðamerkurjökull, which will raise the average reflectance values of the pixels they occupy. It was therefore assumed that the highest TSS sampled (0.58 g L\(^{-1}\)) was a maximum for the lagoon, and that the corresponding reflectance value (0.13) was a maximum for non-ice-occupied water. The visual survey of the lagoon that was undertaken during in-situ measurements suggests that this is a reasonable assumption. B1 greyscale images were then subsetted to the Jökulsárlón water surface using the Landsat-derived AOI, and pixels with a reflectance >0.13 were masked in order to remove high values likely to reflect iceberg presence. The location most consistently masked was close to the tidal inlet/outlet, where icebergs become grounded in shallow water.

Table 1. Plume and associated environmental descriptive statistics for all days on which usable MODIS images are available: acquisition time (UTC), air temperature (\(T_a\)), rainfall in 24 h up to acquisition time (\(P_{24}\)), Positive Degree Hours (\(\Sigma PDH\)), cumulative from 1 April 2012, tidal tendency (\(\Delta tide\)), wind direction (\(D_w\)), meridional wind velocity (\(V_w\); positive is offshore, negative is onshore), proportional lagoon coverage by floating ice (%ice), proportional lagoon coverage by turbid plume (%plume), minimum Total Suspended Solids (TSS) value in plume (TSS\(_{\text{min}}\)), mean TSS value in plume (TSS\(_{\text{mean}}\), standard deviation of TSS values in plume (TSS\(_{\text{SD}}\)).

<table>
<thead>
<tr>
<th>Date</th>
<th>Acq(_t) time</th>
<th>(T_a) (°C)</th>
<th>(P_{24}) (mm)</th>
<th>(\Sigma PDH)</th>
<th>(\Delta tide) (m h(^{-1}))</th>
<th>(D_w) (°)</th>
<th>(V_w) (m s(^{-1}))</th>
<th>%ice</th>
<th>%plume</th>
<th>TSS(_{\text{min}}) (g L(^{-1}))</th>
<th>TSS(_{\text{mean}}) (g L(^{-1}))</th>
<th>TSS(_{\text{SD}}) (g L(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 Apr</td>
<td>12:32</td>
<td>5.4</td>
<td>1.0</td>
<td>1407</td>
<td>-0.045</td>
<td>No data</td>
<td>No data</td>
<td>22.6</td>
<td>0.000</td>
<td>0.000</td>
<td>0.124</td>
<td>0.129</td>
</tr>
<tr>
<td>26 Apr</td>
<td>12:38</td>
<td>3.2</td>
<td>215</td>
<td>1977</td>
<td>0.000</td>
<td>215</td>
<td>35.1</td>
<td>35.1</td>
<td>0.090</td>
<td>0.150</td>
<td>0.045</td>
<td>0.139</td>
</tr>
<tr>
<td>27 Apr</td>
<td>13:21</td>
<td>8.1</td>
<td>9.9</td>
<td>2039</td>
<td>-0.201</td>
<td>28</td>
<td>0.96</td>
<td>0.96</td>
<td>0.015</td>
<td>0.139</td>
<td>0.000</td>
<td>0.139</td>
</tr>
<tr>
<td>02 May</td>
<td>13:55</td>
<td>9.7</td>
<td>3006</td>
<td>3006</td>
<td>-0.131</td>
<td>11</td>
<td>2.05</td>
<td>2.05</td>
<td>0.000</td>
<td>0.147</td>
<td>0.000</td>
<td>0.147</td>
</tr>
<tr>
<td>12 May</td>
<td>12:20</td>
<td>3.6</td>
<td>3509</td>
<td>3509</td>
<td>0.147</td>
<td>13</td>
<td>7.35</td>
<td>7.35</td>
<td>0.000</td>
<td>0.164</td>
<td>0.000</td>
<td>0.164</td>
</tr>
<tr>
<td>11 May</td>
<td>12:51</td>
<td>7.6</td>
<td>3721</td>
<td>3721</td>
<td>0.164</td>
<td>24</td>
<td>3.69</td>
<td>3.69</td>
<td>0.000</td>
<td>-0.155</td>
<td>0.000</td>
<td>-0.155</td>
</tr>
<tr>
<td>15 May</td>
<td>11:56</td>
<td>11.2</td>
<td>3879</td>
<td>3879</td>
<td>-0.155</td>
<td>172</td>
<td>-0.74</td>
<td>-0.74</td>
<td>0.000</td>
<td>-0.104</td>
<td>0.000</td>
<td>-0.104</td>
</tr>
<tr>
<td>15 May</td>
<td>13:09</td>
<td>3.0</td>
<td>4465</td>
<td>4465</td>
<td>-0.104</td>
<td>351</td>
<td>10.04</td>
<td>10.04</td>
<td>0.000</td>
<td>-0.080</td>
<td>0.000</td>
<td>-0.080</td>
</tr>
<tr>
<td>16 May</td>
<td>12:14</td>
<td>4.3</td>
<td>4512</td>
<td>4512</td>
<td>-0.191</td>
<td>6</td>
<td>9.15</td>
<td>9.15</td>
<td>0.000</td>
<td>-0.158</td>
<td>0.000</td>
<td>-0.158</td>
</tr>
<tr>
<td>28 May</td>
<td>12:38</td>
<td>13.9</td>
<td>6649</td>
<td>6649</td>
<td></td>
<td>22</td>
<td>2.50</td>
<td>2.50</td>
<td>0.000</td>
<td>0.009</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>30 May</td>
<td>12:26</td>
<td>8.2</td>
<td>7069</td>
<td>7069</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. (a) Wavelength vs. reflectance for different values of Total Suspended Solids (TSS, g L\(^{-1}\)), showing the consistent response in MODIS band 1 (B1), which is indicated by grey shading. (b) Wavelength vs. TSS-reflectance correlation, showing the consistent, high values in B1. (c) Regression of TSS on in-situ reflectance (ref) in a 620–670 nm window, equivalent to B1. The regression equation, \(TSS = 4.7004\text{ref}\), is used to calibrate MOD09GQ imagery to TSS values, as described in the text.
The B1 calibration and high-value mask were used to map TSS variability in Jökulsárlón for all cloud-free days up to the end of May 2012. A potential change in the form of the TSS–reflectance relationship is anticipated as runoff to the lagoon increases significantly in the main melt season, June–September. The time series is not therefore extended into that period, since there is evidence for significant seasonality in the hydrographic properties and processes of Jökulsárlón. Brandon and others (2013) and Voytenko and others (2015a) found comparable lagoon water temperatures (0.5–2.5°C) in spring and summer 2012, respectively. However, summer salinities (7–17 psu) were lower than in spring (15–21 psu), indicating a clear dilution effect from summer melting and runoff. Moreover, Brandon and others (2013) observed Gade slopes in springtime temperature-salinity plots (Gade, 1979), denoting submarine melting at the terminus of Breiðamerkurjökull, whereas in summer Voytenko and others (2015a) did not, concluding as a result that there was a seasonal shift in melting from mainly ocean forcing in winter and spring, to mainly atmosphere forcing in summer and autumn.

Eleven clear-sky days yielded usable imagery, covering the period 19 April–30 May. MOD09GQ images were used for all days except 2 May, when the MOD09GQ image was cloud-affected so an MYD09GQ image was used instead. All images used were acquired within a daily 2 h window ~1300 coordinated universal time (UTC; Table 1). Figure 3 shows TSS maps for the days, which exhibited the lowest (19 April) and highest (7 May) mean values of plume TSS. Also shown for the same days is the proportion of Jökulsárlón that is covered by an identifiable plume, which is not co-linear with TSSmean (mean of all unmasked pixels, TSSmean) is greater at the end of the observation interval than at the start, there is no significant trend in that variable either (TSSmean = 0.017 + 0.0013d, R² = 0.11, p = 0.33). However, minimum plume TSS (TSSmin) which is not co-linear with TSSmean does increase significantly in the same interval (TSSmin = 0.0030d – 0.34, R² = 0.52, p = 0.01). Correlations between the plume variables, tides and meteorology are presented in Table 2. In general, there are few simple associations between the series. For instance, there are no significant correlations between air temperature, 24 h precipitation or tidal tendency and any TSS metrics. Further, there is no association between the plume-covered proportion of the lagoon and tidal tendency.

DISCUSSION

Time series of plume variables, tides and meteorology are presented in Figure 4. Plume metrics such as area and length have previously been measured as proxies for hydrologic outputs from the land to the ocean (Thomas and Weatherbee, 2006; Halverson and Pawlowicz, 2008; Lihan and others, 2008) but not often for glacially-fed plumes (Chu and others, 2009; McGrath and others, 2010; Hudson and others, 2014). The proportion of Jökulsárlón that is covered by an identifiable plume (%plume) varies between 23 and 98% over the interval considered (Table 1), but with no significant temporal trend (%plume = 0.0057–0.24d, R² = 0.08, p = 0.41, where d is Day of Year). Likewise, although mean TSS (mean of all unmasked pixels, TSSmean) is higher on 7 May (Fig. 3).

Fig. 3. (a) Plume extent and TSS distribution, 19 April 2012, the day of lowest TSSmean. (b) Plume extent and TSS distribution, 7 May 2012, the day of highest TSSmean.

 particularly the west margins. There are also turbid, terrestrial river inputs to the lagoon, again from the east and especially the west margins. This corresponds to the pattern observed in-situ. Riverine inputs have a glacial origin and are not distinguishable from submarine inputs in this analysis. There are further high TSS values adjacent to the tidal inlet, where strong turbulence is encountered in shallow water (<20 m). This fundamental spatial pattern is essentially unchanging over the period studied, although the relative contributions of these various sources change significantly, with turbid inputs from the east margin of Breiðamerkurjökull, for example, being notably high on 7 May (Fig. 3).
The only variables with which TSS\textsubscript{mean} is significantly correlated are \%\textsubscript{plume} and $V_w$ (positive correlations in both cases; Table 2). The standard deviation of plume TSS ($TSS_{\sigma}$), on the other hand, is not significantly correlated with \%\textsubscript{plume}, but is significantly, positively correlated with the ice-covered proportion of the lagoon (%ice, simply quantified as those pixels with reflectance > 0.13). \%\textsubscript{plume} is also significantly, negatively correlated with both $\Sigma PDH$ and wind speed (Table 2). $TSS_{\sigma}$ also exhibits a strong, negative correlation with $TSS_{\text{min}}$ but this is a constraint of the threshold mask used to define maximum plume TSS. Maximum plume TSS is not therefore a very useful metric, but the $TSS_{\text{min}}$ threshold is only used to define the plume extent, not to constrain TSS values, and is more useful as a result. In fact, $TSS_{\text{min}}$ exhibits correlations that suggest the plume metrics do capture the pre-melt-season evolution of the lagoon: $\Sigma PDH$ is significantly, positively correlated with $TSS_{\text{min}}$, while %ice is significantly, negatively correlated with it (Table 2). This suggests that MODIS-derived metrics are credibly representing rising overall turbidity in the lagoon as melting accumulates.

The lack of correlation between $\Sigma PDH$ and $TSS_{\text{mean}}$ may be influenced by the application of the maximum TSS threshold, but this is not likely to be the only influence. TSS is controlled by sediment availability, which is limited (Hodgkins and others, 2003). Therefore, maximum TSS will increase seasonally only to a certain level before stabilising or even declining as sediment supplies diminish. As this occurs, changes in total sediment fluxes are likely to be expressed through changes in plume extent, rather than in plume TSS values. Indeed, Chu and others (2009) observed seasonal hysteresis between ice-sheet melt extent and plume area.

---

**Table 2.** Pearson product-moment correlation coefficient, $r$, for plume and associated environmental descriptive statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>$TSS_{\text{mean}}$</th>
<th>$TSS_{\sigma}$</th>
<th>$TSS_{\text{range}}$</th>
<th>$TSS_{\text{min}}$</th>
<th>%ice</th>
<th>%plume</th>
<th>$T_a$</th>
<th>$P_{24}$</th>
<th>$\Sigma PDH$</th>
<th>$\Delta t$</th>
<th>$D_w$</th>
<th>$V_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TSS_{\text{range}}$</td>
<td>-0.47</td>
<td>0.87</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$TSS_{\text{min}}$</td>
<td>0.54</td>
<td>-0.91</td>
<td>-0.95</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%ice</td>
<td>-0.33</td>
<td>0.72</td>
<td>0.55</td>
<td>-0.72</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%plume</td>
<td>0.86</td>
<td>-0.55</td>
<td>-0.75</td>
<td>0.74</td>
<td>-0.33</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Sigma PDH$</td>
<td>0.28</td>
<td>-0.66</td>
<td>-0.52</td>
<td>0.69</td>
<td>-0.83</td>
<td>0.21</td>
<td>0.42</td>
<td>-0.34</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_w$</td>
<td>0.65</td>
<td>-0.62</td>
<td>-0.65</td>
<td>0.68</td>
<td>-0.38</td>
<td>0.84</td>
<td>-0.59</td>
<td>-0.13</td>
<td>0.17</td>
<td>0.32</td>
<td>0.20</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Significant values ($p < 0.05$) are in bold, potentially co-linear values are in italics. Rows in which no significant correlations occur have been omitted.
suggesting late-season, sediment-supply exhaustion. This emphasises the value of our linear reflectance-TSS calibration, which can be used to map values of TSS and suggests that the approach taken here, of basing the maximum reflectance threshold on high, ice-proximal TSS values observed in April, is reasonable, as it is unlikely that sediment supply and therefore maximum TSS will markedly increase as the melt season progresses.

The temporal trend in %ice is significant (%ice = 77.103–0.0019d, R² = 0.69, p = 0.00) and it is negatively associated with ∑PDH (r = −0.83; Table 2), but this is probably explained by the circulation of icebergs around and out of the lagoon, rather than by melt processes: in particular, a cluster of icebergs in the southwest of Jökulsárlón moves anti-clockwise to the outlet and largely disperses over the course of the observed interval, accounting for most of the ice-cover decrease. Voytenko and others (2015b) noted that the large-scale circulation within Jökulsárlón was mostly clockwise, but that there was also the occasional formation of small-scale, anti-clockwise eddies near the shore, of which the movement of this iceberg cluster is probably an example.

The cloudiness associated with an extended period of rainfall gives an 11 d gap in the MODIS series from 16 May. TSS values are lower (TSSmean 0.19 g L⁻¹) than those pre-gap (TSSmean 0.25 g L⁻¹) when the data resume (Table 1, Fig. 4). Melt rates tend to be low during rainfall, as cloudiness reduces receipts of solar radiation; this is despite rising air temperatures at Kvísker, where the persistent cloud cover contributes to a reduced diurnal temperature range. A plausible interpretation of the reduced post-gap TSS is that the extended period of recession flow during the days of cloud and rainfall reduces sediment entrainment, and therefore also the volume and turbidity of runoff to the lagoon in late May, though values are still higher than at the beginning of the observation interval in late April. Actual runoff from Breiðamerkurjökull, being mostly subaerial, is unknown. While Tg and ∑PDH are reasonable proxies for melt rates and cumulative melt respectively, neither are satisfactory proxies for runoff itself due to the complexity of the glacier drainage system, with its time-varying storage properties (e.g. Hodgkins and others, 2013).

As plumes disperse down a fjord or estuary, their characteristics are often increasingly influenced by tides (Bowers and others, 1998; Halverson and Pawlowicz, 2008) and winds (Stumpf and others, 1993; Whitney and Garvine, 2005). Dowdeswell and Cromack (1991) found that plume extent in Sognefjorden, Svalbard, was tidally dominated; wind speed and direction had little influence in the small (<1 km²), sheltered inlet they studied. However, in the much larger Kangerlussuaq Fjord, West Greenland, Chu and others (2009) noted that the tidal influence on plume extent was negligible, as shown by nearly-identical plume-extent probability-distribution functions during incoming and outgoing tides. Any effect of tides on plume formation in Jökulsárlón is potentially affected by a constraining effect on water leaving the lagoon, but not on entering it (Tinder, 2012). This produces a more rapid rise in water level during the rising tide and a slower decrease during the falling tide.

Vw here is significantly correlated with all the plume metrics, but to the greatest degree (and positively) with %plume. The 3 d of strongest winds coincide with the 3 d of greatest plume extent (Fig. 4). The wind direction on all of these days is offshore (351°–13°). There are 2 d when the MODIS image is acquired during onshore winds (172°–215°) but these do not correspond with notably low %plume – which might be expected, given that strong offshore winds correspond with high %plume. However, onshore winds are somewhat weaker than offshore ones, with mean onshore velocities at the time of image acquisition being 0.71 m s⁻¹ (corresponding to a meridional wind stress of 0.001 kg m⁻¹ s⁻²), compared with offshore velocities of 4.87 m s⁻¹ (meridional wind stress 0.038 kg m⁻¹ s⁻²).

The influence of tidal tendency on the extent of the plume is therefore quantifiably less than that of the wind regime: Δtide is negative on two of the three largest plume days, but strongly positive on the other, while Vw is consistently high on all three. This also suggests that the constricting effect of falling tides probably does not have an important influence on plume extent. Whitney and Garvine (2005) indicated that moderate-to-strong winds could modify the width of a large, coastal river plume significantly, and even overwhelm the general, buoyancy-driven flow. With reference to simple calculations by Voytenko and others (2015b), katabatic wind speeds measured on Breiðamerkurjökull are sufficient to sustain a wind-driven circulation within the surface waters of Jökulsárlón: wind speeds about half the magnitude of the offshore ones can account for most of the observed surface current speeds.

CONCLUSIONS

This study demonstrates that MODIS band 1 reflectance (620–670 nm) can successfully be related to TSS values for a tidewater glacier meltwater outflow plume. Similar relationships have previously been identified (e.g. Chu and others, 2009; Hudson and others, 2014), but this study differs in applying to a specific overturning plume at a calving face, as opposed to plumes derived from subaerial, glacially-fed river runoff, or to fjord systems as a whole. Furthermore, the simple, single-band calibration at Jökulsárlón is linear, without the signal saturation identified in some other studies from glacial environments. This requires application of an in-situ-sampling-constrained threshold to determine plume extent, but aids water quality mapping, in that a wider range of plume metrics can be determined, for example, pixel-by-pixel TSS and statistical measures of its variability, instead of simply an index of its presence or absence. The 250 m-resolution of the MODIS imagery does not impose any apparent limitations in this 23 km² lagoon system: the remotely-identified spatial variability of the turbid plume corresponds to that observed in situ. Significant trends in several plume metrics are readily identified in the pre-melt-season interval for which the calibration can confidently be applied. Plume extent responds principally to forcing by surface winds, as tidal influence appears limited in the lagoon, and the offshore wind regime of the Breiðamerkurjökull area is consistently strong.

Further work should determine the plume’s inter- and intra-annual variability, and water-source discrimination (e.g. subglacial vs. subaerial inputs). Plumes hold potential, if not necessarily as proxies for runoff, then as indices of hydrological outputs, in large-scale, ungauged or ungate-able systems. Results from Jökulsárlón suggest that remote studies of plumes also have potential for quantifying sediment fluxes, though further work is required to determine the degree of any (presumably location-specific) relationship
between plume extent and depth: previous, oceanographic
studies of plumes in glacial fjords (e.g. Cottier and others,
2005; Sciascia and others, 2013) suggest that stratification
is sufficiently consistent that this is probably feasible.

ACKNOWLEDGEMENTS

G. Gisladóttir, Veðurstofa Íslands, supplied the Kvísker
weather data. F. Pálsson, Institute of Earth Sciences,
University of Iceland, supplied the Breiðamerkurjökull
weather data. Financial support was provided by the
School of Social, Political and Geographical Sciences,
Loughborough University, by the Open University, and by
the Percy Sladen Memorial Fund, Linnean Society of
London. J. Chandler, Department of Civil and Building
Engineering, Loughborough University, provided access to
Erdas Imagine. J.A. Runólfsón, Jökulsárlón ehf, was an ex-
tremely helpful Zodiac pilot. The constructive comments of
Allen Pope and an anonymous reviewer led to significant
improvements to the original manuscript.

REFERENCES

Arendt KE and 6 others (2011) Effects of suspended sediments
on copepods feeding in a glacial influenced sub-Arctic fjord. J.
Bergström S and 31 others (2007) Impacts of climate change on river
runoff, glaciers and hydropower in the Nordic area. Joint Final
Report from the CE Hydrological Models and Snow and Ice

Björnsson H and Pálsson F (2008) Icelandic glaciers. Jökull, 58,
365–386

Björnsson H, Pálsson F and Gudmundsson S (2001) Jökulsárlón at
Breiðamerkursandur, Vatnajökull, Iceland: 20th century
changes and future outlook. Jökull, 50, 1–18.

fine suspended sediments in the surface waters of the Irish Sea
and its relation to tidal stirring. Int. J. Remote Sens., 14, 2789–
2805

Hydrographic measurements in Jökulsárlón lagoon, Iceland.

Chen S and 5 others (2015) Estimating wide range Total Suspended
Solids concentrations from MODIS 250-m imageries: an
improved method. ISPRS J. Photogramm. Remote Sens., 99,


Chu VW and 5 others (2009) Sediment plume response to surface
melting and supraglacial lake drainages on the Greenland

Chu VW, Smith LC, Rennermalm AK, Forster RR and Box JE (2012)
Hydrologic controls on coastal suspended sediment plumes
around the Greenland ice sheet. Cryosphere, 6, 1–19 (doi:
10.5194/tc-6-1-2012).

Church JA and 13 others (2013) Sea level change. In Storck TF and
10 others eds. Climate change 2013: the physical science basis.
Contribution of working group I to the fifth assessment report of
the intergovernmental panel on climate change. Cambridge
University Press, Cambridge, UK and New York, NY, USA.

Cottier F and 5 others (2005) Water mass modification in an Arctic
fjord through cross-shelf exchange: the seasonal hydrography
of Kongsfjorden, Svalbard. J. Geophys. Res., 110(C122005)

Curran PJ and Novo EMM (1988) The relationship between sus-
pended sediment concentration and remotely sensed spectral ra-

Dowdeswell JA and Cromack M (1991) Behavior of a glacier-
derived suspended sediment plume in a small Arctic inlet.
J. Geol., 99, 111–123.

Spectral signature of highly turbid waters: application with
SPOT data to quantity suspended particulate matter concentra-
S0034-4257(01)00341-8).

Gade HG (1979) Melting of ice in sea water: a primitive model with
application to the Antarctic ice shelf and icebergs. J. Phys.
009<0189:MOISW>2.0.CO;2).

plume by river flow and tides. J. Geophys. Res., 113(C09033)

sediment fluxes in a high-Arctic glacierised catchment: implica-

Hodgkins R, Cooper R, Tranter M and Wadhams J (2013) Drainage-
system development in consecutive melt seasons at a polyther-
mal, Arctic glacier, evaluated by flow-recession analysis and

Hu C and 5 others (2004) Assessment of estuarine water-quality indi-
cators using MODIS medium-resolution bands: initial results
from Tampa Bay, FL. Remote Sens. Environ., 93(3), 423–441

Hudson B and 5 others (2014) MODIS observed increase in duration
and spatial extent of sediment plumes in Greenland fjords.
Cryosphere, 8(4), 1161–1176 (doi: 10.5194/c-8-1161-2014)

Jóhannesson H (1994) Coastal erosion near the bridges across
Jökulsá á Breiðamerkursandi in southeastern Iceland. In
Viggósson G ed. Proceedings of the international coastal sympos-

Jóhannesson T and 14 others (2007) The impact of climate change on
European Conference of Impacts of Climate Change on
Renewable Energy Sources, Reykjavík, Iceland.

Jóhannesson T and 13 others (2007) Effect of climate change on hy-
drology and hydro-resources in Iceland. Final Report of the
VO-Project, OS–2007/011.

Joughin I, Alley R and Holland D (2012) Ice-sheet response to
science.1226411).

Lihan T, Saitoh S-T, Iida T, Hirawake T and Iida K (2008) Satellite-
measured temporal and spatial variability of the Tokachi River
plume. Estuarine Coastal Shelf Sci., 78(2), 237–249 (doi:

McGrath D and 5 others (2010) Sediment plumes as a proxy for local
ice-sheet runoff in Kangeralussuq Fjord, West Greenland.

Miller RL and McKee BA (2004) Using MODIS Terra 250 m imagery
to map concentrations of total suspended matter in coastal
waters. Remote Sens. Environ., 93(1–2), 259–266 (doi:

variability of submarine melt rate and circulation in an East
10.1002/jgrc.20142).

derived dissolved and colloidal iron to the coastal ocean and
implications for primary productivity. Global Biogeochem. Cy.,

Straneo F and 15 others (2013) Challenges to understand the
dynamic response of Greenland’s marine terminating glaciers
(doi: 10.1175/BAMS-D-12-00100.1)

forcing of a buoyant plume, Mobile Bay, Alabama. Cont. Shelf
Res., 13(11), 1281–1301.


Tinder P (2012) *Ocean-ice interactions at Breiðamerkurjökull glacier, Southeast Iceland*. (Unpublished MSc thesis, Ohio State University, USA)


