1 Measurement and modeling of ablation of the bottom
2 of supraglacial lakes in western Greenland

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13 [1] We report measurements of ablation rates of the bottom
14 of two supraglacial lakes and of temperatures at different
15 depths collected during the Summers of 2010 and 2011 in
16 west Greenland. To our knowledge, this is the first time
17 that such data sets are reported and discussed in the
18 literature. The measured ablation rates at the bottom of the
19 two lakes are of the order of ~6 cm/day, versus a rate of
20 ~2.5–3 cm/day in the case of bare ice of surrounding areas.
21 Though our measurements suggest the presence of a
22 vertical temperature gradient, it is not possible to draw final
23 conclusions as the measured gradient is smaller than the
24 accuracy of our temperature sensors. In-situ measurements
25 are compared with the results of a thermodynamic model
26 forced with the outputs of a regional climate model. In
27 general, the model is able to satisfactorily reproduce the
28 measured quantities with RMSE of the order of 3–4 cm for
29 the ablation and ~1.5°C in the case of water temperature.
30 Our results confirm that the ablation at the bottom of
31 supraglacial lakes plays an important role on the overall
32 lake volume with the ablation in the case of bare ice covered by
33 a lake being 110–135% of that over bare ice at nearby
34 locations. Beside ice sheet hydrological implications,
35 melting at the bottom of a supraglacial lake might affect
36 estimates of lake volume from spaceborne visible and near-
37 infrared measurements. Citation: Tedesco, M., M. Lüthje,
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1. Introduction and Background

2 [2] Supraglacial lakes form annually in topographic
3 depressions of the surface of the Greenland ice sheet (GrIS
4 e.g., Selmes et al., 2011), affecting ice loss through
5 increased surface ablation and, during drainage, affecting
6 basal water pressures and ice velocities [e.g., Lüthje et al.,
7 2006; Das et al., 2008; Pimentel et al., 2010; Sundal et al.,
8 2011] Over the past years, several studies have estimated
9 the area and volume of supraglacial lakes from spaceborne
10 observations [e.g., Sneed and Hamilton, 2007; Box and Ski,
11 2007; McMillan et al., 2007] and some have been able to
12 validate these estimates from ground based measurements
13 [Tedesco and Steiner, 2011; Sneed and Hamilton, 2011].
14 [3] Very little is known about the contribution of the
15 melting of the bottom of supraglacial lakes to their total
16 volume, with this aspect being generally neglected in studies
17 dealing with volume estimates. This is possibly due to the
18 absence of in-situ observations, which can be used to
19 understand the physical processes involved or to validate
20 theoretical models. To fill this gap, here we report mea-
21 surements of ablation rates of the bottom of two supraglacial
22 lakes collected during the Summers of 2010 and 2011 in
23 West Greenland. Temperature values were also collected at
24 different depths within the lakes to study the vertical distri-
25 bution of water temperature (being this an important factor
26 for understanding, modeling and quantifying convection rate
27 at lake bottom). To our knowledge, this is the first time that
28 such data sets are reported and discussed in the literature.
29 In-situ measurements are compared with the outputs of a
30 fully physically-based thermodynamic model which, in turn, is
31 forced with the outputs from a regional atmospheric
32 model, coupled with a snow model.

3 [4] In-situ measurements confirm the crucial role played
33 by supraglacial lakes in enhancing ice ablation and suggest
34 the presence of a vertical temperature gradient within the
35 lake. Model’s outputs compare favorably with measure-
36 ments. In the following we discuss the methods used to
37 collect the data, the measured quantities and the comparison
38 between modeled and measured values of both ablation rates
39 and lake water temperature.

2. In-Situ Measurements

5 The ablation rate of the bottom of a supraglacial lake
6 (ABL R hereafter) is obtained from the data recorded by two
7 pressure transducers, with the first (top) sensor being firmly
8 secured at a fixed height to an aluminum pole drilled in the
9 ice where a supraglacial lake is assumed to form. The
10 second (bottom) sensor is loosely attached to the same pole
11 and resting on the ice surface so that it can slide down-
12 wards following the ice bottom along the pole as the bot-
13 tom of the lake melts, while still remaining close to the pole
14 (see Figure S1 in the auxiliary material). The ABLR is
15 then calculated from the difference between the time series
16 of the depths recorded by the two sensors. The depth

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1Auxiliary materials are available in the HTML. doi:10.1029/2011GL049882.
In this case, the top sensor was initially positioned 0.7 m above the bottom one. The two sensors were underwater from June 14th and the lake drained on June 19th. All sensors recorded pressure and temperature every five minutes on an internal data logger and were recovered following lake drainage. The sensors have a water level (temperature) absolute accuracy of ~0.5 cm (~0.35°C) and a resolution of ~0.21 cm (~0.1°C) around 0°C, see http://www.onsetcomp.com/files/manual_pdf/12315-D-MAN-U20.pdf). For each lake, pressure data were corrected for altitude and for barometric pressure changes using data collected by a third pressure sensor located in close proximity (within 1 km) of the lake.

3. Modeling Tool

We model the ABLR and water temperature using a one-dimensional enthalpy approach model [Alexiades and Solomon, 1993]. In the following we give a brief description of the model and refer the reader to Lüthje et al. [2006] for more details. The volume of ice down to a depth Z is divided into N control volumes, with the volumes being initialized with an enthalpy corresponding to a temperature profile with a depth gradient of 2 K · m⁻¹, based on measurements from Pakitsoq, West Greenland [Lüthje et al., 2006]. The model accounts for conductive heat transport through ice following Alexiades and Solomon [1993]. Turbulent heat transfer through lake water is also accounted for. The heat flux between the turbulent lake and the ice bottom is computed using the ‘four thirds’ law [Linden, 2000]. Here, the turbulent heat flux is proportional to the four thirds power of the temperature difference between the core temperature of the lake and the upper boundary temperature. The model is forced with the net energy flux at the interface between surface and atmosphere. Specific inputs are surface air temperature, shortwave incoming radiation, albedo, atmospheric pressure, incoming and outgoing longwave radiation, latent heat and sensible heat fluxes. These are obtained from the Modèle Atmosphérique Régional (MAR) model, a regional atmospheric model coupled with a snow [e.g., Fettweis et al., 2011; Tedesco et al., 2011]. The ERA-INTERIM reanalysis (2002–May 2011) and the operational analysis (June 2011 – to date) data from the European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/) are used to initialize the meteorological fields and to force the lateral boundaries every 6 hours. Note that ECMWF fields are used only at the boundaries of the region containing the GrIS (see Fettweis [2007] for details) and that the inputs to the ablation model are obtained from the atmospheric model within MAR. MAR outputs are produced at a horizontal spatial resolution of 25 km and their accuracies have been assessed over the GrIS [e.g., Fettweis et al., 2011]. To further investigate the potential use of MAR outputs to satisfactorily drive the ablation model, a comparative analysis of MAR outputs with in-situ measurements available from the GC-Net stations is reported in the auxiliary material (Figure S2).

4. Results

Figure 1 shows the time series of the lake depth measured by the top and bottom sensors in the case of Lake Bluesnow (Figure 1a) and Lake Ponting (Figure 1b). In the
The difference between the depths measured by the bottom and top sensors is also plotted. This difference is interpreted as the ablation of the bottom of the lake (see Figure S1 for an explanatory diagram) and it is compared to the outputs of the thermodynamic model described in the previous section.

Figure 2 shows the comparison between measured and simulated ABLR (Figures 2a and 2c) and water temperatures (Figures 2b and 2d) for Lake Bluesnow and Lake Ponting. Continuous black lines in Figures 2a and 2c refer to the temperature measured by the top sensor where the temperature measured by the bottom sensor is indicated by the dashed black lines. Gray lines with disks indicate simulated values when considering 2 m (Lake Bluesnow) and 0.7 m (Lake Ponting) initial water level where gray lines with squares indicate simulated values in the case of bare ice.

In-situ measurements show that the total measured ablation for the bottom of Lake Bluesnow (Ponting) for the period when both sensors were underwater (~5 days in both cases) is ~0.25 m (~0.33 m) with a linear trend of 6.2 cm/day (5.7 cm/day). Ablation of bare ice over the same period obtained from GC-Net sonic ranger measurements is ~0.12 m (0.14 m) in the case of the Swiss Camp (JAR-1) station. Our measurements confirm that the ablation in the case of bare ice is considerably smaller than that measured when the lakes are present. The values of the final ABLR measured at Lakes Bluesnow and Ponting are, respectively, 2.1 (110%) and 2.35 (135%) times greater than those estimated from GC-Net measurements over bare ice at nearby locations, in agreement with Lüthje et al. [2006].

From the analysis of the temperature data, we observe that, in general, the top sensors record lower temperature values (dashed line in Figures 2b and 2d) than those measured by the bottom sensors. However, it is not possible to affirm that an actual vertical temperature gradient exists within the water column because the temperature differences between the top and bottom sensors are within the accuracy of the temperature sensor. The time series of the temperatures recorded by the two sensors also indicate that shifts in the relative position of the maxima and minima daily temperature exist (e.g., days 178–179 at Lake Bluesnow). A possible cause of this might be the fact that the vertical distance between the two sensors within the lake changes with time (as a consequence of the sinking of the bottom sensor). However, it is not possible to formulate any conclusive...
hypothesis with the data at our disposal and more measure-
ments could help understanding this issue.

[13] When comparing modeled and measured quantities, for Lake Bluesnow we obtain a rate of 5.4 cm/day when considering an initial water level of 2 m (versus a measured value of 6.2 cm/day) and an RMSE between the measured and simulated ablation values of 4.7 cm. For Lake Ponting we obtain a modeled ablation rate of 5.74 cm/day with an initial water level of 0.7 m (versus a measured value of 6.8 cm/day) and an RMSE of 3.2 cm. In contrast to Lake Bluesnow, the model outputs for Lake Ponting are more sensitive to the different considered initial water levels. This is because the values of the initial water level for Lake Ponting are smaller than those we use in the case of Lake Bluesnow. For both lakes, discrepancies between modeled and measured ABLR might be due to intrinsic limitations of the model (e.g., knowledge of physical processes and their implementation) and to the uncertainty associated with the atmospheric forcing generated with the MAR model. We will evaluate the sensitivity of the thermodynamic model to the input parameters by perturbing the MAR outputs within a range that will be decided based on the relative error between measured and simulated quantities. Factors extrin-
sic to the model can also be responsible of the differences between the measured and simulated values. For example, the presence of patchy snow and/or of cryoconite at the bottom of the lake (observed during fieldwork activities) affects the albedo of the bottom of the lake. This aspect is not accounted for in our model but it will, however, affect the measured ABLR.

[14] Temperature values simulated by the model for Lake Bluesnow are consistent with observed values for the first two days of the observational period. For the remaining five days the model generally tends to overestimate the water temperature and the RMSE for the whole period between measured and simulated top (bottom) temperatures (considering an initial water level of 2 m) is 1.64°C (1.59°C). Conversely, the model tends to underestimate the observed water temperature at the beginning of the observation period in the case of the Lake Ponting, to perform better over the last three days, with an overall RMSE of 1.23°C (1.18°C) in the case of the temperature measured by the top (bottom) sensor. One possible explanation of the differences between the simulated and measured temperatures is that the model treats the lake as a closed system that heats up, excluding the influx of melt water from the surrounding areas which would eventually cool the water within the lakes.

5. Conclusions

We reported in-situ measurements of the ablation rate at the bottom of two supraglacial lakes on the GrIS, together with water temperatures measured at two different depths within the lakes. In agreement with results obtained from previous studies using modeling tools, our measurements indicate that the ablation rate at the bottom of a supraglacial lake is about two times that of an equivalent nearby bare ice surface. To our knowledge, this is the first time that this is proved through observations, confirming the importance of such lakes for ice sheet surface ablation and hydrological processes. The measured daily ablation rate at the bottom of the two lakes was of the order of ~6 cm/day, versus a rate of ~2.5–3 cm/day in the case of bare ice. Measured ablation rates at the bottom of the two lakes were compared with those obtained from a physical model forced with the outputs of a regional atmospheric model coupled with a snow physical model. In general, the model was able to satisfac-
torily reproduce the measured ablation rates, with RMSE values of 4.7 and 3.2 cm, respectively.

[16] We also reported measurements concerning the vertical profile of water temperature. Observed differences between the temperatures measured at different depths were smaller than the accuracy of the temperature sensors, hence making it impossible to draw any conclusion. The model was generally capable of reproducing the water temperature (assumed to be uniform in the model), though overestima-
tion by the model occurred.

[17] The results reported in this study confirm that the ablation at the bottom of supraglacial lakes can play an important role on the overall lake volume. For example, in the case of Lake Ponting the overall depth of the lake increased by ~3 m during the period when both sensors were underwater, of which 0.33 m due to the melting of its bottom. This can be especially important for those lakes whose lifetime is relatively long, especially those that do not drain during a melt season [Selmes et al., 2011]. Melting at the bottom of a supraglacial lake might also be expected to alter its reflective properties, with implications for satellite-based techniques used to estimate lake volume from visible and near-infrared observations [e.g., Sneed and Hamilton, 2007]. Such techniques assume that the reflective prop-
erties of the bottom of the lake are the same as those of the areas along the lake shore. Given the different ablation rates between bare and water-covered ice, the assumption adopted in the satellite-based techniques might introduce error on the lake volume estimates if the optical properties of the ice exposed at the bottom of the lake are different from those at the lake’s edge. Moreover, studies investigating ice sheet surface hydrology processes, and in particular those modeling runoff and streamflow, should account for the ablation of the bottom of the lakes. The general agreement between measured and modeled quantities for the two lakes studied in this paper suggests that it would be possible to account for this quantity by forcing the ablation model used in this study with outputs from the MAR model.

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