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

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[1] We report measurements of ablation rates of the bottom of two supraglacial lakes and of temperatures at different depths collected during the summers of 2010 and 2011 in west Greenland. To our knowledge, this is the first time that such data sets are reported and discussed in the literature. The measured ablation rates at the bottom of the two lakes are of the order of ∼6 cm/day, versus a rate of ∼2.5–3 cm/day in the case of bare ice of surrounding areas. Though our measurements suggest the presence of a vertical temperature gradient, it is not possible to draw final conclusions as the measured gradient is smaller than the accuracy of our temperature sensors. In-situ measurements are compared with the results of a thermodynamic model forced with the outputs of a regional climate model. In general, the model is able to satisfactorily reproduce the measured quantities with RMSE of the order of 3–4 cm for the ablation and ∼1.5°C in the case of water temperature. Our results confirm that the ablation at the bottom of supraglacial lakes plays an important role on the overall lake volume with the ablation in the case of ice covered by a lake being 110–135% of that over bare ice at nearby locations. Beside ice sheet hydrological implications, melting at the bottom of a supraglacial lake might affect estimates of lake volume from spaceborne visible and near-infrared measurements. **Citation:** Tedesco, M., M. Lüthje, K. Steffen, N. Steiner, X. Fettweis, I. Willis, N. Bayou, and A. Banwell (2012), Measurement and modeling of ablation of the bottom of supraglacial lakes in western Greenland, *Geophys. Res. Lett.*, *39*, LXXXXX, doi:10.1029/2011GL049882.

1. Introduction and Background

[2] Supraglacial lakes form annually in topographic depressions of the surface of the Greenland ice sheet (GrIS) [e.g., *Selmes et al.*, 2011], affecting ice loss through increased surface ablation and, during drainage, affecting basal water pressures and ice velocities [e.g., *Lüthje et al.*, 2006; *Das et al.*, 2008; *Pimentel et al.*, 2010; *Sundal et al.*, 2011] Over the past years, several studies have estimated the area and volume of supraglacial lakes from spaceborne observations [e.g., *Sneed and Hamilton*, 2007; *Box and Ski*, 2007; *McMillan et al.*, 2007] and some have been able to validate these estimates from ground based measurements [*Tedesco and Steiner*, 2011; *Sneed and Hamilton*, 2011].

[3] Very little is known about the contribution of the melting of the bottom of supraglacial lakes to their total volume, with this aspect being generally neglected in studies dealing with volume estimates. This is possibly due to the absence of *in-situ* observations, which can be used to understand the physical processes involved or to validate theoretical models. To fill this gap, here we report measurements of ablation rates of the bottom of two supraglacial lakes collected during the summers of 2010 and 2011 in West Greenland. Temperature values were also collected at different depths within the lakes to study the vertical distribution of water temperature (being this an important factor for understanding, modeling and quantifying convection rate at lake bottom). To our knowledge, this is the first time that such data sets are reported and discussed in the literature. *In-situ* measurements are compared with the outputs of a fully physically-based thermodynamic model which, in turn, is forced with the outputs from a regional atmospheric model, coupled with a snow model.

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

2. *In-Situ* Measurements

[5] The ablation rate of the bottom of a supraglacial lake (*ABLR* hereafter) is obtained from the data recorded by two pressure transducers, with the first (top) sensor being firmly secured at a fixed height to an aluminum pole drilled in the ice where a supraglacial lake is assumed to form. The second (bottom) sensor is loosely attached to the same pole and resting on the ice surface so that it can slide downwards following the ice bottom along the pole as the bottom of the lake melts, while still remaining close to the pole (see Figure S1 in the auxiliary material).[1] The ABLR is then calculated from the difference between the time series of the depths recorded by the two sensors. The depth

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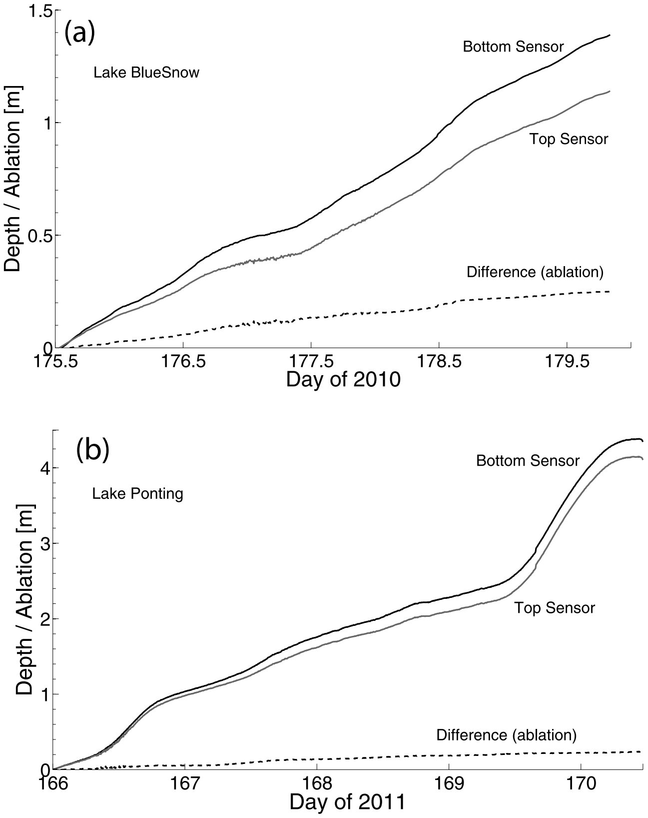

Figure 1. Lake depth measured by the top (gray continuous lines) and bottom (black continuous lines) sensors at (a) Lake Bluesnow and (b) Lake Ponting and their difference (dashed black line).

measured by the top sensor is indeed the height of the water column above the sensor while the depth measured by the bottom sensor is the depth measured by the top sensor plus the original height difference between the two sensors plus the thickness of the ice lost from the bottom of the lake, where the sensor is sitting. The ablation rate can therefore be obtained from the difference in the slopes of the curves describing the filling rates measured by the two sensors (Figure S1). One assumption underlying this technique is that the aluminum pole does not considerably sink into the ice. The analysis of our data shows that this is a reasonable assumption, as the vertical displacements of the poles that are within the ice for relativealy short periods (~5–10 days) were found to be considerably smaller than the measured ablation rates.

[6] *In-situ* data were collected during the summers of 2010 and 2011 at two different locations in west Greenland. The first pair of sensors was deployed on May 17th, 2010 nearby (~200 m) the Swiss Camp station of the Greenland Climate Network (69.569 N, −49.342 E, 1149 m a.s.l., GC-Net) [*Steffen et al.*, 1996] where satellite images and in-situ surveys indicated a lake would form annually (Lake Bluesnow hereafter). The top sensor was initially located 2 m above the bottom one. The lake filled on June 10th and both sensors were underwater from June 23rd. The lake drained on June 28th. The second pair of sensors was deployed ~10 km north of the JAR-1 GC-Net station on June 13th, 2011 (69. 589 N, −49.783 E, 962 m a.s.l., Lake Ponting hereafter). 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.

[7] 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_pdfs/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

[8] 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 $2\ \mathrm{K} \cdot \mathrm{m}^{-1}$, based on measurements from Pâkitsoq, 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 model [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

[9] 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

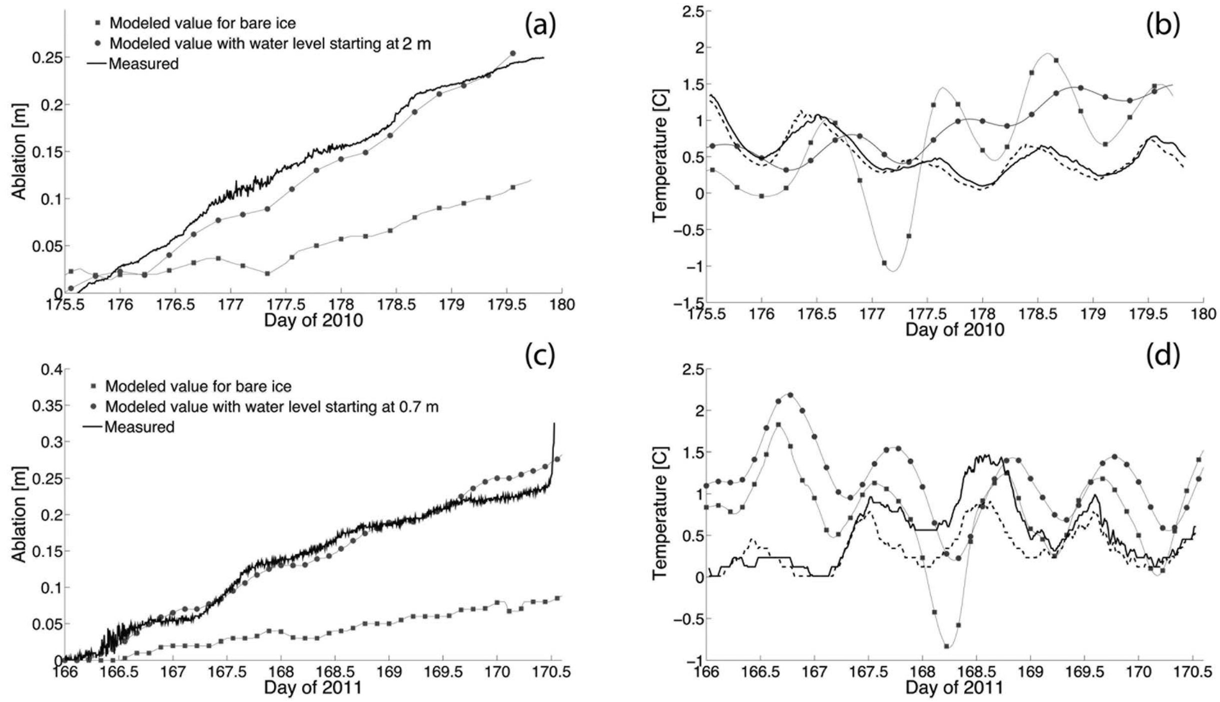

Figure 2. Measured and simulated ABLR (Figures 2a and 2c) and water temperatures (Figures 2b and 2d) for (a, b) Lake Bluesnow and (c, d) Lake Ponting. Continuous black lines in Figures 2a and 2c show the measured ABLR. Continuous black lines in Figures 2c and 2d refer to the temperature measured by the 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.

figure, 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.

[10] Figure 2 shows the comparison between measured and simulated ABLR (Figures 2a and 2c) and water temperatures (Figures 2b and 2d) for Lake Bluesnow (Figures 1a and 2b) and Lake Ponting (Figures 2c and 2d). In Figures 2a and 2c, continuous black lines show the measured ABLR. In Figures 2b and 2d, continuous black lines refer to the temperature measured by the top sensor where the dashed black lines indicate the temperature measured by the bottom sensor. As mentioned above, the top sensors were located respectively 2 m (Lake Bluesnow) and 0.7 m (Lake Ponting) above the ice surface when they were deployed. Therefore, in our simulations we assume these values to be the initial water level in the lake to compare modeled and measured ablation rates (gray lines with disks). For reader's convenience, we also show in Figure 2 the simulated ablation in the case of bare ice (gray lines with squares). We point out that the values for the initial water level used in our simulations might not account for the ablation occurring during the period when the bottom sensor was underwater but the top sensor was not (on the order of 1–2 days).

[11] *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 Blusenow 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].

[12] From the analysis of the temperature data, we observe that, in general, the bottom sensors record lower temperature values (dashed line in Figures 2b and 2d) than those measured by the top 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 measurements 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 perturbating the MAR outputs within a range that will be decided based on the relative error between measured and simulated quantities. Factors extrinsic 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 three 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 overestimate the measured 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 tend to cool the water within the lakes.

5. Conclusions

[15] 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 satisfactorily 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 overestimation 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 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 properties 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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