INTEGRATION OF REMOTE SENSING WITH A HYDROCLIMATOLOGICAL MODEL FOR AN IMPROVED MONITORING OF ALPINE GLACIERS

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ABSTRACT

In this work, we present a framework to integrate physically based hydroclimatological models and remote sensing products, by exploiting their advantages and overcoming their limitations, for an improved understanding and estimation of the alpine glacier accumulation and ablation processes. The capability of remote sensing to well represent the spatial variability of the snow cover over the glaciers is used to correct possible errors in the model simulations, thus obtaining a more reliable estimation of annual glacier mass balance. The proposed approach is tested on the glaciers in the Rofen Valley (Austria) by employing the AMUNDSEN model for accumulation and ablation processes simulation and Landsat-5/7/8 data for glacier zone mapping from 1998 to 2016.

Index Terms— Glacier mass balance, hydroclimatological model.

1. INTRODUCTION

The mass balance of a glacier is the sum of all processes that add and remove mass from a glacier over some specified periods. The annual mass balance represents a change in water storage in the catchment and is therefore an important hydrological measure. Moreover, the loss or gain of glacier mass is a direct response of a glacier to climatic conditions and thus constitutes a key indication of climate change [1].
The physically based hydroclimatological model AMUNDSEN (Alpine MUltiscale Numerical Distributed Simulation ENgine) has been designed to specifically address the scenario-capable modelling of hydrological and climatological processes in mountain regions. It can be employed for modelling cryosphere processes such as accumulation, ablation and ice redistribution on glaciers and can thus simulate annual mass balance. The model has recently been applied and validated in a variety of geographical and climatological settings [2], [3].
On the other hand, satellite imagery can provide reliable mapping of the accumulation and ablation zones, i.e. part of the glacier with positive and negative mass balance respectively, through high resolution multi-spectral images such as Landsat or Sentinel-2 [4]. The main limitation of this remote sensing application is the impossibility to reveal the water equivalent lost or gained during one year for each pixel. On the other side, the binary spatial information of positive and negative mass balance at the instant of the acquisition can be very reliable and has also been used in many cases as hydrological model product validation (e.g. [2]).
The aim of this study is to propose an automatic classification method for glacier zone mapping from high resolution multi-spectral satellite data (i.e. Landsat and Sentinel-2) and to employ this product in combination with the hydroclimatological model to get reliable glacier mass balance estimation.
While reliable glacier zone remote sensing maps can be obtained with some manual interactions [4], in this study we present an unsupervised classification method for automatically generate snow cover maps over the glaciers, thus allowing to extend the method over wide areas and long-time spans. By assuming that areas which are snow covered throughout the year are part of the accumulation zone and areas which are snow free are part of the ablation zone, we can use these thematic maps to derive a spatial information on positive and negative mass balance distribution.
By exploiting the glacier zone maps obtained from remote sensing, we propose two methods to correct the modeled glacier mass balance: 1) correction on disagreement, and 2) spatial distributed correction. Results on the glacier mass balance obtained with the proposed approach are compared and validated with ground based data for a set of glaciers located in the Rofen Valley (Austria).

2. HYDROCLIMATOLOGICAL MODEL AND REMOTE SENSING INTEGRATION METHOD FOR GLACIER MASS BALANCE ESTIMATION

The proposed approach is formed by two main steps: 1) remote sensing glacier zone classification and 2) glacier mass balance correction through remote sensing.

2.1. Remote sensing glacier zone classification

The proposed method detects snow cover on glaciers based on multi-temporal Landsat satellite imagery in conjunction with a supplied glacier inventory. All Landsat satellite imageries are atmospherically and topographically corrected (Ekstrand correction). By using the glacier masks a histogram of the Eckstrand corrected NIR band from each glacier is derived. Subsequently, an individual threshold for each single glacier is automatically selected (Otsu thresholding method). This ensures specific thresholding for each glacier and each Landsat image to obtain the most suitable detection of snow cover on glaciers. The results indicate mapping accuracy of about 90%.

The part of the glaciers with no snow cover is then assumed as ablation zone, thus characterized by a negative mass balance. The part of the glaciers covered by snow is likely to be characterized by a positive mass balance (i.e. accumulation zone), but could be ablation zone in some cases if the snow detected is older than one year, i.e. firn, or if ablation processes are followed by new snowfall, i.e. the glacier is covered by fresh-snow. This has to be considered when exploiting the remote sensing product for the modelled glacier mass balance correction.

Further developments are in progress to implement a robust classifier that is able to distinguish different snow types, i.e. old-snow, firn, fresh-snow, thus improving the remote sensing glacier zone classification product.

2.2. Glacier mass balance correction through remote sensing

The obtained remote sensing glacier zone maps (section 2.1) are then used to correct the hydroclimatological simulated maps of the AMUNDSEN model and thus to estimate the glacier mass balance. The AMUNDSEN model provides for each pixel of a glacier, the amount of snow/firn/ice water equivalent and the amount of water equivalent gained or lost during a predefined period of time (i.e. the mass balance).

2.2.1. Correction on disagreement

This method consists of finding a mass balance correction for only those pixels for which the information of the remote sensing maps disagrees with the information of the hydroclimatological model. Given the remote sensing maps described in section 2.1, a disagreement can occur in two cases. The first case occurs when, for a certain pixel, either snow water equivalent (swe) or firn water equivalent (fwe) simulated by the model is higher than zero and the remote sensing product detects ablation (i.e. no snow). By taking as true the remote sensing information, this implies that the model is overestimating the mass balance and thus the correction is:

$$\Delta B_{i,t} = -(swe_{i,t} + fwe_{i,t}) \qquad (1)$$

where $\Delta B_{i,t}$, is the glacier mass balance correction, $swe_{i,t}$ and $fwe_{i,t}$ are the swe and fwe simulated by the model at the pixel i, where by notation i stands for a 2-dimensional coordinate, and at a time instant t correspondent to the satellite acquisition.

The second case of disagreement occurs when both the swe and the fwe simulated by the model are equal to zero and the remote sensing method detects accumulation (i.e. snow cover). This case is evaluated only at the time instant t_m corresponding to the minimum snow cover over the glacier. In this way, we assume that the snow cover is never caused by fresh snow covering an area where previous firn or ice melting occurred. Thus, by considering the remote sensing information as true, the glacier mass balance correction is:

$$\Delta B_{i,t_m} = -B_{i,t_m} \qquad (2)$$

where B_{i,t_m} is the mass balance simulated by the model at the pixel i and time instant t_m.

For all the cases of agreement between remote sensing and model, as well as the cases of disagreement in which the remote sensing product detect snow cover at time instant $t \neq t_m$, $\Delta B_{i,t} = 0$.

Once all the $\Delta B_{i,t}$ are computed for each pixels and each time instants for which a remote sensing information is available, the correction on the annual mass balance ΔAB_i can be computed for each pixel as the sum between the minimum negative correction, i.e. the instant for which the model simulate the maximum accumulation while disagreeing with the remote sensing information and the positive correction computed at the time instant t_m corresponding to the minimum snow cover over the glacier:

$$\Delta AB_i = \min_t\{\Delta B_{i,t}, 0\} + \max\{\Delta B_{i,t_m}, 0\} \qquad (3)$$

In this way, when, for a certain pixel i the model tends to overestimate accumulation or melting throughout the year, $\Delta B_{i,t}$ will be always negative or positive for each t, thus either $\min_t\{\Delta B_{i,t}, 0\}$ or $\max\{\Delta B_{i,t_m}, 0\}$ will be equal to zeros. On the other hand, if the overestimation of accumulation or melting changes in time and these problems are detected from the remote sensing product, positive and negative corrections may be both not equal to zeros, thus balancing themselves.

2.2.2. Spatial distributed correction

The aim of this method is to find a mass balance correction distributed in space, i.e. not only limited to the points for which model and remote sensing disagree. This is done by correcting the modelled mass balance map $\boldsymbol{m}_t$, simulated at the time t, through a generic parametric function $f(\boldsymbol{m}_t, \boldsymbol{c}_t)$, where $\boldsymbol{c}_t$ is the vector of the parameters characterizing the function f. The best correction, i.e. the optimum $\boldsymbol{c}_t$ vector, is then found by maximizing the agreement between the binary map of snow cover generated from the corrected model and the remote sensing glacier zone map:

$$\begin{cases} \tilde{\boldsymbol{m}}_t = f(\boldsymbol{m}_t, \boldsymbol{c}_t) \\ \boldsymbol{c}_t = \underset{\boldsymbol{c}_t}{\operatorname{argmin}} \sum_i w_{i,t} \cdot \left|\operatorname{sgn}\left(s_{i,t} + \tilde{m}_{i,t} - m_{i,t}\right) - r_{i,t}\right| \end{cases} \tag{4}$$

with

$$s_{i,t} = \begin{cases} swe_{i,t} + fwe_{i,t}, & \text{if } swe_{i,t} + fwe_{i,t} > 0 \\ B_{i,t}, & \text{otherwise} \end{cases} \tag{5}$$

where $\tilde{m}_{i,t}$ is the corrected mass balance at pixel i, $swe_{i,t}$ and $fwe_{i,t}$ are the swe and fwe simulated by the model at pixel i, $r_{i,t}$ is 1 for accumulation and -1 for ablation in the remote sensing map acquired at time t, i.e. the same day of the model simulation, $w_{i,t}$ is the weight related to the uncertainty of the remote sensing classification pixel. $w_{i,t}$ could be set equal to 1 for each pixel if the uncertainty of the remote sensing product is not available.

By applying this correction, the snow cover area in the remote sensing product is assumed equal to the accumulation area: a non-snow pixel in the binary snow cover map generated from the model can be converted in snow through the correction only when the mass balance turns to be positive. This may cause some errors when the snow detected by the remote sensing product is firn or fresh-snow. To limit the possibility of fresh-snow occurrence, the correction is only applied for the date in which the remote sensing map detect the minimum snow cover over the glacier. The found correction is then applied to the modelled mass balance simulated at the end of the ablation period to estimate the corrected annual mass balance.

The simplest parametric correction function to be chosen is:

$$f(\boldsymbol{m}_t, \boldsymbol{c}_t) = \boldsymbol{m}_t + c_t \tag{6}$$

This corresponds to the assumption that the water equivalent mass balance modelled map is wrong by a bias only, which is constant for all the pixels of the glacier. Testing of more complex correction function (i.e. spatially non-constant) are under development.

3. STUDY AREA AND DATASET

We test our approach over the glaciers of the Rofen Valley (Austria) for the period from 1998 to 2016. Within this period, we use the snow/firn/ice water equivalent map time series simulated with the AMUNDSEN model, from which annual glacier mass balance can be computed. The remote sensing data employed for glacier zone mapping are Landsat-5, Landsat-7 and Landsat-8 images.

Long-term annual mass balance records are available for three glaciers in the Rofen Valley: Hintereisferner, Vernagtferner and Kesselwandferner. They are used for validation of the simulated specific annual mass balance. Furthermore, glacier surface elevation changes as found from two DEM acquisitions in 1997 and 2006 are available for comparison.

4. RESULTS

We evaluated the performances of the proposed approach by comparing the annual mass balance of the Hintereisferner measured by the World Glacier Monitoring Service (WGMS) with the annual mass balance simulated by the AMUNDSEN model and estimated through the two proposed correction methods: correction on disagreement and spatial distributed correction (i.e. bias correction) (Fig. 1).

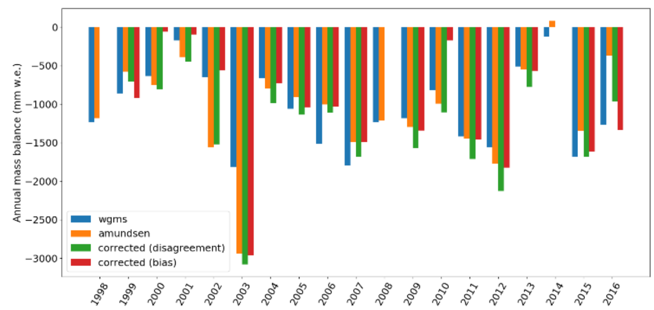

Fig. 1. Comparison between the annual glacier mass balance of the Hintereisferner measured by the WGMS (taken as reference), simulated with the AMUNDSEN model and corrected with the correction on disagreement and bias correction methods.

An example of the correction on the mass balance operated with the proposed approach is presented in Fig. 2, where the corresponding false color composite generated from Landsat-7 data (Fig. 2a) and the respective snow cover classification map (Fig. 2b) are also shown. Both correction methods improve the overall root mean square error (RMSE) and the R^2 taking the WGMS measurements as reference. The best overall performances are obtained by using the bias method, which provides a RMSE equal to 397 mm and a R^2 of 0.86 (Tab. I)

TABLE I
MASS BALANCE ESTIMATION PERFORMANCES (HINTEREISFERNER)

	RMSE (mm)	R^2
AMUNDSEN	477	0.66
Correction on disagreement	473	0.76
Bias correction	397	0.86

5. CONCLUSIONS

In this paper, we introduced an approach to integrate hydroclimatological models and remote sensing thematic maps to improve glacier mass balance estimation. The preliminary results show that the glacier zone remote sensing product can be successfully employed to correct some overestimation or underestimation in the glacier accumulation or ablation processes in the

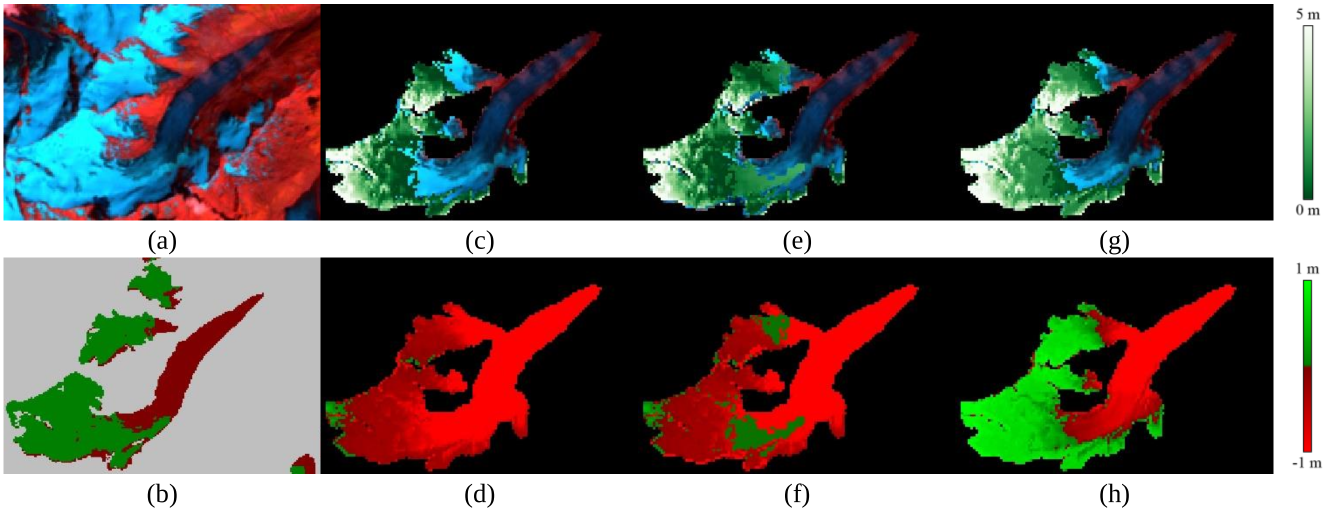

Fig. 2. Example of glacier mass balance correction on the Hintereisferner, using the model simulation and the Landsat-7 image acquired on August 20th, 2002. (a) shows the false color composite of the Landsat-7 data, obtained using the SWIR (red channel), NIR (green channel) and green (blue channel) spectral bands; (b) glacier zone map obtained by [5]: green corresponds to the snow cover zone, red to ablation zone, gray to no data. Figure (c) and (d), (e) and (f), (g) and (h) show the sum between the swe and fwe and the mass balance as simulated by the model, corrected through the proposed correction on disagreement and through the proposed bias correction method respectively.

hydroclimatological model simulations. Further analyses and developments are in progress, such as: 1) Improve the remote sensing glacier zone classification to allow the discrimination of different snow types: i.e. fresh-snow, old-snow, firn; 2) Develop a classification algorithm for Sentinel-2 data to increase the temporal frequency of the remote sensing glacier zone maps since 2015; 3) Develop a more complex spatial distributed correction method, which does not imply a spatially constant correction; 4) Enlarge the validation to other glaciers and datasets.

The proposed approach is conceived as a general methodology and could be therefore easily extended to wider areas and longer time period, i.e. since the first Landsat-5 images are available (1985).

6. ACKNOWLEDGMENTS

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