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# Global-scale modeling of glacier mass balances for water resources assessments: Glacier mass changes between 1948 and 2006

Yukiko Hirabayashi [a,*], Petra Döll [b], Shinjiro Kanae [c]

[a] Institute of Engineering Innovation, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
[b] Institute of Physical Geography, Frankfurt University, P.O. Box 111932, 60054 Frankfurt am Main, Germany
[c] Department of Mechanical and Environmental Informatics, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552, Japan

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ABSTRACT

Glaciers play an important role for freshwater resources, but in global-scale freshwater assessments, their impact on river flows has not yet been taken into account. As a first step, we developed a global glacier model that can be coupled to global land surface and hydrological models. With a spatial resolution of 0.5° by 0.5°, the glacier model HYOGA computes glacier mass balance by a simple degree-day approach for 50 m sub-grid elevation bands, modeling all glaciers within a grid cell as one glacier. The model is tuned individually for each grid cell against observed glacier mass balance data. HYOGA is able to compute glacier mass balances reasonably well, even those of summer accumulation type glaciers. Still, model uncertainty is high, which is, among other reasons, due to the uncertainty of global data sets of temperature and precipitation which do not represent well the climatic situation at glacier sites. We developed a 59-yr (1948–2006) time series of global glacier mass balance and glacier area by driving HYOGA with daily near-surface atmospheric data. According to our computations, most glaciers have lost mass during the study period. Compared to estimates derived from a rather small number of observed glacier mass balances, HYOGA computes larger glacier mass losses in Asia, Europe, Canadian Arctic islands and Svalbard. In accordance with the estimates, average annual mass losses have increased strongly after 1990 as compared to the 30 yrs before. The sea level equivalent of the melt water from glaciers is 0.76 mm/yr water equivalent after 1990 as compared to only 0.34 mm/yr water equivalent before. We computed an acceleration of glacier mass losses after 1990 for all world regions except South America, where the number of gauge observations of precipitation is very small after 1980.



## 1. Introduction

According to the most recent estimate of Dyurgerov and Meier (2005), glaciers and ice caps cover 540,000 ± 30,000 km$^2$ outside of Antarctica and Greenland, less than 0.4% of the global land area. Nevertheless, they play an important role in water availability in many river basins. Seasonal water storage in glaciers and ice caps is beneficial for downstream aquatic ecosystems and human water users, as melted ice augments low flows during the warm and dry season. Hereafter, we use the term glaciers to refer to mountain glaciers and ice caps outside of Antarctica and Greenland.

According to Lemke et al. (2007), most glaciers have been shrinking mainly due to air temperature increases, many of them already since 1850. Exceptions are the glaciers in Norway and New Zealand, where glacier mass increased in the 1990s due to increased precipitation, but since the year 2000, glaciers have been shrinking there also. Glacier mass development is driven by the surface mass balance (the gain or loss of snow, firn and ice over a certain time period) or ice calving, while the mass balance at the glacier bed (loss due to basal melting) is negligible at global or regional scales (Lemke et al., 2007). At a rate of 0.63 ± 0.18 mm/yr water equivalent during 1991–2004, glacier mass loss is estimated to have contributed approximately twice as much to global sea level rise than the melting of the much larger Antarctic and Greenland ice sheets (Lemke et al., 2007). Future climate change is expected to accelerate glacier shrinkage for most glaciers as precipitation increases cannot balance increased melting due to higher temperatures (Meehl et al., 2007).

Most global-scale mass balance estimates for glaciers have been based on direct mass balance observations at about 300 glaciers that were up-scaled by area-weighted averaging or spatial interpolation (Lemke et al., 2007) whereas more than 70,000 glacier locations are recorded in the World Glacier Inventory (WGI), which is collected mainly by the World Glacier Monitoring Service (WGMS), Zurich, and more than 130,000 glaciers are inventoried in Cogley (2009). With a total area of 34,000 km$^2$, these 300 glaciers represent only about 6% of the global glacier area. Cogley and Adams

* Corresponding author. Tel.: +81 3 5841 0716.
*E-mail address:* hyukiko@sogo.t.u-tokyo.ac.jp (Y. Hirabayashi).

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(1998) indicated that the method of estimating glacier mass balance by interpolating limited mass balance data lead to a bias. This is due to uneven spatial coverage of observations, because measured glaciers are often small and are commonly located at low elevations due to better accessibility as compared to high elevation glaciers. The total global volume of glaciers outside of Antarctica and Greenland is highly uncertain, with estimates ranging from 51,000 to 166,000 km$^3$ (Lemke et al., 2007; Radić and Hock, 2010).

Several previous studies estimated current variations and future development of glacier mass using numerical mass balance models. For example, Radic and Hock (2006) developed a mass balance glacier model of Storglaciären in Sweden and projected future glacier mass development. Verbunt et al. (2003) applied their numerical snow and glacier model to estimate time series of glacier volume in Alpine river basins. Rees and Collins (2006) showed the effect of climate warming on discharge in glacier-fed Himalayan Rivers, using a three-dimensional glacier model coupled with a hydrological model. Huss et al. (2008) developed a distributed mass balance and glacier evolution model and applied the model to assess the impact of climate change on runoff from three highly glacierized catchments in Switzerland. However, these studies treated a limited number of glaciers with mostly well-observed mass balances. In a global-scale study, Raper and Braithwaite (2006) estimated the impact of climate change on glacier mass by first estimating the 1961–1990 average mass balance in 1° grid cells, using modeled glacier mass balances in seven glacier regions with good mass balance observation and a multiple regression of gradients of mass balance versus altitude on global gridded estimates of long-term average precipitation and summer temperature. Then they scaled their computed 1961–1990 global mass balance to match the previous estimate, and projected the future global mass balance using temperature projections from two different climate models. Hock et al. (2009) also used a modeling approach to obtain global and regional scale glacier mass balance estimates for the period 1961–2004, based on modeled mass balance sensitivities to temperature and precipitation changes as well as long-term temperature and precipitation trends obtained from reanalysis.

To estimate the impact of glaciers on river discharge worldwide, it is necessary to determine not only long-term average annual glacier mass balances but daily or monthly time series. Only such time series will make it possible to better estimate the impact of climate change on seasonal low flows and droughts in glacier-fed river basins. In modeling studies that did not take into account glaciers, many glacier-fed river basins were projected to suffer from increases in drought frequency induced by climate change (e.g. Hirabayashi et al., 2008a; Lehner et al., 2006). To the best of our knowledge, no numerical mass balance models have been developed up to now that can provide gridded sub-annual time series of glacier mass changes for the whole globe.

The aim of the study presented here is to develop a global glacier model for estimating daily gridded time series of glacier mass balances, suitable for supporting global water resources assessments. The output of our new global glacier model HYOGA ("glacier" in Japanese) can be used to drive global hydrological or land surface models. This will allow us, for the first time, to assess the impact of glaciers on freshwater resources at the global scale, also under conditions of climate change. Since a high percentage of irrigated areas are located in glacier-fed river basins, HYOGA also has the potential to improve global food security assessments. Besides, model results could also be used for estimating the contribution of glaciers to sea level rise.

In the following section, we first describe the model and its input data, and then show how the model was initialized and calibrated such that the time series of glacier mass balance between 1948 and 2006 could be computed. In Sections 3 and 4, modeled glacier mass changes are presented, and model uncertainties are discussed. In Section 5, we summarize our work and draw conclusions.

## 2. Methods

### 2.1. Model description

The global glacier model HYOGA is driven by time series of daily precipitation and near-surface temperature and computations are performed using daily time steps. The horizontal spatial resolution of HYOGA is 0.5° by 0.5° as most global hydrological models, and many climate data sets, share this resolution. All glaciers within each grid cell are modeled as one equivalent glacier, the area of which is the sum of the areas of all glaciers within the grid cell. Volume-area scaling is used to estimate glacier volume from (observed) glacier area, and to update glacier area after the computation of glacier mass and thus volume changes after each time step.

Mass balances of snowpack and glacier ice are determined in 50 m sub-grid elevation bands, using a simple degree-day approach to compute melting. Within each grid cell, the air temperature is assumed to decrease with increasing altitude, with a constant lapse rate of −0.65 °C/100 m. This value was determined by comparing 63 modeled and observed glacier mass balances at different elevation bands (observations provided by WGMS). With this value, which is equal to the value used by Braithwaite and Raper (2007), it was possible to obtain modeled equivalent line altitudes that are similar to observed values. Like temperature, precipitation varies with altitude, but these variations are very site specific, depending, among others, on wind direction and orography. Therefore, it is not possible to use a uniform precipitation lapse rate, and a suitable approach for determining precipitation lapse rates for global-scale studies does not exist yet. Thus, precipitation was assumed to be the same in all elevation bands of a grid cell. Potential orographic effects on precipitation amount are however indirectly adjusted via the calibration process explained in Section 2.3.2.

#### 2.1.1. Mass balances

HYOGA includes two mass balance modules: a snowpack module which simulates the accumulation and melting of snow as well as the transformation of snow into glacier ice, and a glacier module which computes the volume of melted glacier ice using a simple degree-day approach. The mass balance of the snowpack in the $i$th elevation band (Fig. 1) is computed in terms of equivalent liquid water volume as

$$\begin{aligned} Sn_i(t+\Delta t) &= Sn_i(t) + Snf_i(t) - G_i - M_{si} \\ M_{si} &= (T_i - T_0)\cdot DDF_{snow} \text{ if } T_i > T_0 \\ & \quad 0 \text{ otherwise} \end{aligned} \tag{1}$$

where $Sn_i$ is water equivalent of snowpack, $t$ is time, $\Delta t$ is 1 day, $Snf_i$ is snowfall, $G_i$ is the volume of water that is transformed from snow into glacier ice, $M_{si}$ is volume of melted snow, $T_0$ is a critical temperature for snow melting, $T_i$ is surface temperature at the sub-grid elevation band height and $DDF_{snow}$ is the degree-day factor of the snowpack. $T_0$ was set to 0 °C, while $DDF_{snow}$ was adjusted by calibration (see Section 2.3.2). We assume that only precipitation that falls as snow affects the snowpack balance. If HYOGA is linked to a hydrological model, rainfall on glaciers immediately becomes runoff. Precipitation is assumed to fall as snow if air temperature of the elevation band is less than or equal to 2 °C. This threshold was used because it leads to similar global snowfall amounts as a more sophisticated method that considers humidity (Hirabayashi et al., 2008c). One year after snowfall is incorporated into the snowpack, it is transformed into glacier ice (Fig. 1). Thus, firn is not taken