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What glaciers are telling us about Earth's changing climate

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Abstract

A glacier monitoring system has been developed to systematically observe and document changes in the size and extent of a representative selection of the world's 160 000 mountain glaciers (entitled the PTAAGMB Project). Its purpose is to assess the impact of climate change on human societies by applying an established relationship between glacier ablation and global temperatures. Two sub-systems were developed to accomplish this goal: (1) a mass balance model that produces daily and annual glacier balances using routine meteorological observations, (2) a program that uses Google Maps to display satellite images of glaciers and the graphical results produced by the glacier balance model. The recently developed PTAA glacier balance model is described and applied to eight glaciers to produce detailed mass balance reports. Comparing annual balances produced by the model to traditional manual measurements for 50–60 years yields R^2 values of 0.50–0.60. The model also reveals an unusual but statistically significant relationship between the average ablation of Wrangell Range glaciers and global temperatures that have been derived from temperature data at 7000 stations in the Northern Hemisphere. This glacier ablation/global temperature relationship provides the means to use worldwide ablation results to anticipate problems caused by climate change.

1 Introduction

Glaciers are extraordinarily sensitive to climate variations, making relatively large changes in size and extent (a measure of mass balance) in response to a small change in the climate. A substantial change in the climate, such as has occurred during the past several decades, is causing many of them to disappear entirely. Measuring the mass balance (the difference between snow accumulation and snow and ice ablation) of a glacier is labor intensive and expensive – only a few dozen of the world's approximately 160 000 glaciers are measured consistently (Meier and Bahr, 1996). A glacier monitoring system is developed and will be applied to a representative selection of forty glaciers. A recently developed mass balance model is applied that produces daily balances for each glacier at each altitude interval using routine precipitation and temperature observations collected at one or two weather stations in the region. The PTAA model (precipitation-temperature-area-altitude) has been tested for glaciers in Alaska, Washington, Austria and Nepal. Comparison of measured annual balances with those produced by the model yields R^2 values for linear regressions that range from 0.20 to 0.67. The main advantages of this model are that it is inexpensive to apply, it produces daily and annual mass balances (for the net, ablation and accumulation components) and its approximate accuracy is known. In addition, the balance as a function of elevation is calculated for each component. It resembles a degree-day model only in its weather data requirements but does not require manual balances for calibration.

2 Mass balance measurements (background)

Conventional methods for measuring mass balance have been well developed since the pioneering work of Swedish glaciologists (Williams et al., 2012; Holmlund and Jansson, 1999; Ahlmann, 1953). The original field manuals for making mass balance measurements on a glacier (Ostrem and Stanley, 1966), were updated by Ostrem and Brugman (1991). Early work by Hoinkes and others measuring the mass balance of glaciers in the Austrian Alps laid the foundation for manual measurement techniques (Hoinkes, 1955). Recent advancements in reporting and documenting glacier fluctuations have been made by the World Glacier Monitoring Service (2011), based on research by Haberli (2007, 2011) and Zemp (2009). Recent analyses of mass balance measurements have been made for the 1945–2003 period by Dyurgerov et al. (2005). Satellite photogrammetry and airborne lidar permits differencing between digital-elevation models (DEMs) to calculate mass balance from volume changes between mappings (the geodetic balance method) (Bauder et al., 2006; Haakensen, 1986). The mass balance of the Greenland and Antarctic ice sheets is of great concern because continuous

negative balances will result in a rise in global sea level (Rignot and Thomas, 2002). Negative glacier balances and the disappearance of glaciers also create problems for millions of people who rely on glaciers to store water during wet periods and release it when the weather is hot and dry.

3 The PTAA mass balance model

3.1 Model description

The PTAA model (Precipitation-Temperature-Area-Altitude) is dependent on the climate history that is embedded in the glacier's surface configuration (its area-altitude distribution) and relies on the internal consistency of mass balance variables, for example the relationship between snowline elevation and glacier balance. Detailed explanations of the model and how it functions are provided in Tangborn (1997, 1999, 2013), and Tangborn and Rana, (2000).

In the PTAA model, snow and ice ablation is calculated at each elevation interval from the observed daily mean temperature and the diurnal temperature range, based on the temperature lapse rate that is also calculated from temperature observations. Snow accumulation is calculated at each elevation interval from observed precipitation at a regional weather station, times a multiplier that is determined from the observed temperature and the lapse rate. If temperature is less than 0 °C, precipitation occurs as snow; if the temperature is greater than 0 °C it occurs as rain. (See simulation model structure in Tangborn, 1999.)

Each calculated value of precipitation and temperature is multiplied by the fraction of total glacier area at each elevation interval (the sum of all fractions = 1.0). The area-altitude distribution of a glacier is a critical aspect of the PTAA model that controls how weather observations are converted to accumulation, ablation and mass balance.

3.2 Model calibration

Coefficients that convert precipitation and temperature observations to snow accumulation and snow and ice ablation are calculated by minimizing the calibration error that is produced by regressing multiple combinations of simulated balance parameters. Figure 1 shows the mean annual balance for the 1951–2012 period for each iteration of the simplex optimizing system, which is a numeric method for solving problems in linear programming (Nelder and Mead, 1965). Figure 2 shows the relationship between mean annual balance and calibration error.

3.3 Monte Carlo similarity

The PTAA model resembles Monte Carlo simulation in that it uses repeated random sampling of calculated coefficients to optimize numerical results. Output from the model are daily snow accumulation (B_c) and ablation (B_a) for each altitude interval, which is converted to mass balance by $B_n = B_c - B_a$. The daily balance is calculated by summing the balance at each area-altitude interval times the fraction of the total glacier area at that altitude. The calculated coefficients are derived from the area-altitude values for each interval but are subject to uncertainties when observed precipitation and temperature are converted to accumulation and ablation. As many as 300 iterations of the simplex (a linear programming technique for solving numerical problems) calculating the daily balance at each altitude interval for 60 years are required to calibrate one glacier. The line plot in Fig. 1 demonstrates the calibration process.

The PTAA model was initially developed and tested for South Cascade Glacier in Washington State (Tangborn, 1999).

3.4 Model applications

The PTAA model has been applied to calculate the mass balance for eight glaciers in Alaska, Washington, Austria and Nepal. Calculated annual balances are compared

with measured balances for approximately 60 years for each of five glaciers (see www.ptaagmb.com). Linear regressions of model vs. measured annual balances yields R^2 values of 0.20 to 0.70 (Table 1). Application of the model to Bering Glacier in Alaska demonstrated a close agreement with ice volume loss for the 1972–2003 period measured with the geodetic method (Tangborn, 2013). The first application of the model was for the rapidly retreating Columbia Glacier in Alaska (Tangborn, 1997). However, manual balance field measurements of Columbia Glacier have not been made, making comparison of model and measured balances impossible. Determining the mass balance and runoff of the partially debris-covered Langtang Glacier in Nepal demonstrates an application of this model to a glacier in the Himalayan Range (Tangborn and Rana, 2000). Simulated ablation for the Langtang Glacier agrees with manual ablation measurements on the nearby Lirung Glacier at the same altitude and on the same day.

Application to the glaciers in the Wrangell Range in Alaska revealed a significant correlation ($r = +0.78$ for a 60 year period) between annual ablation of these glaciers and global temperatures observed at 7000 weather stations in the Northern Hemisphere. These results indicate that glaciers are more sensitive to the global climate than are individual temperature stations, which do not show similar correlations (Tangborn, 2012). The physical relationship between glacier ablation and global temperatures suggests that glaciers can be used to anticipate future climate changes. Annual anomalies of both glacier ablation and global temperatures are shown in Fig. 3.

Balances determined for the Hintereisferner, Vernagtferner and Kesselwandferner in the Austrian Alps for the 1942–2012 period are based on weather observations collected at Innsbruck, Austria, which is approximately 100 km from these glaciers. The relationship between glacier balance and the recent climate change has been developed for these glaciers (Weber et al., 2014).

Comparison of annual balances calculated with the PTAA model and balances determined with a geodetic method for Wrangell Range glaciers show poor agreement for both the 1957–2000 and 2000–2007 periods (Das et al., 2014). The model balances are an order of magnitude more negative than the geodetic balances for both periods.

The cause for such a large disparity is unknown but both methods likely contribute to the difference. By regressing Wrangell glacier vs. Gulkana glacier balances calculated by the model, and measured Gulkana balances vs. simulated Wrangell balances it may be possible to determine the relative error for each method.

4 Glacier ablation and global temperatures

Annual ablation for an average of thirty glaciers in the Wrangell Range is calculated by the PTAA model using daily temperature and precipitation observations collected at McKinley Park and Big Delta located approximately 300 km from these glaciers. The mass balance (accumulation, ablation and net) is determined independently by minimizing the calibration error as described in Tangborn (1999). Annual temperature anomalies averaged for observations at 7000 stations in the Northern Hemisphere by the Hadley Climate Center are correlated with annual ablation for the 1951–2012 period. Both temperature and ablation are referenced to the 1961–1990 mean.

There is a striking similarity in the glacier ablation and global temperature patterns shown as line plots in Fig. 3 that suggests a common cause; the most obvious is variability in the concentration of atmospheric carbon dioxide, which affects both ablation and temperature, but a cause and effect mechanism is not apparent. The dependency of ablation anomalies on global temperature is shown in Fig. 4.

5 Displaying graphical results

The main goal of the PTAAGMB project is to analyze glacier mass balance results to understand and predict climate change. Each of the 200 glaciers planned for the study will respond differently to the global climate and provide useful information for planners who want to mitigate the effects of climate change on human societies. (Forty glaciers are currently in the study and just six have complete reports.) The value of having a graphical display of a large number of glaciers for monitoring is that each glacier

will contribute to a slightly different understanding of how the climate is changing. All of them taken together will provide a unique tool for looking at climate variations. A glacier located in the high Himalayas will respond to a global climate perturbation differently than one located at a low-elevation on Alaska's coast, but together will reveal meteorological subtleties not demonstrated by meteorological instruments or climate models. For example, a change in the global temperature lapse-rate would be apparent from simultaneous analysis of Himalayan and Alaskan glacier mass balances.

The correlation between average ablation of the thirty glaciers in the Wrangell Range and temperature averaged for 7000 weather stations in the Northern Hemisphere provides another example of the value of analyzing a large number of glaciers and temperature stations simultaneously that is easily accomplished by using the graphical display shown on the GMB website.

The information produced each day on the PTAAGMB Project website (www.ptaagmb.com) would be essential to a scientific study analyzing changes in the mass balance of glaciers over a wide geographic range. The website is designed to make glacier research more straightforward and prolific for nearly any region of the earth.

Another goal is to make the research accessible to both the scientific community and the general public. The general public can be distanced from science and often uninterested, so we wanted to make glaciers personally relevant. We did this by including lots of visuals, especially interactive maps and satellite images of glaciers. People can find a glacier perhaps near where they live or have visited, where they have friends or family, or perhaps near a region in which they have other interests.

The website is contained and rendered dynamically in a Content Management System (CMS), to make it relatively easy to post new articles as they develop as more glaciers are added to the GMB website. The CMS system automatically generates new pages, links and menu items as glaciers are added.

Content and chart graphics are placed into a report form in the CMS, to enforce standardized reporting and maintain consistency with the goals of the project. Having a flexible CMS has helped in developing a report structure that accommodates the many variations of glaciers being studied, and the different notable findings in each report, depending on the glacier's type and location.

The display of satellite images on the website is accomplished with the Google Maps JavaScript API. Through that interface, the maps are set to a satellite view, zoomed in to an appropriate level for the size and shape of the area or individual glacier and centered to give the best view in the image area contained at the top of each page.

A marker is then automatically generated on each glacier that shows exactly where the glacier in question is located. Maps are generated for the world, continents, countries, states/regions and each glacier. Each glacier marker is clickable from any map and will pop up a supplemental marker window showing the glacier's name, region and country, and these links are each clickable to navigate to pages showing the area chosen and the glaciers located there.

Navigation through the glacier/map system can be done completely through the images at the top, starting from the home page, or the regional breakdown on the right-hand side, or through "The Glaciers" page. "The Glaciers" page lists all the glaciers contained in the website in alphabetical order, with a complete list on the first page or a subset when a continent, country or state/region is selected.

The country and state/region maps use a street map view to increase personal associations and to better show details like the names of countries, states, cities and roads. At some point, most people will have discovered that there is in fact a glacier being studied in an area of some personal interest to them, and in some cases, the roads to get there.

When an individual glacier marker is selected, the top image view changes to a satellite image, which shows the glacier in its natural state. This image is also convertible to a map view and can be zoomed in or out to show more or less detail.

More information about Google Maps API can be found at https://developers.google.com/maps/web/.

Information about the CMS used can be found at http://umbraco.com/.

6 Conclusions

The world's glaciers provide a unique and reliable gauge of climate variations because they are unusually sensitive to minute changes in temperature, precipitation and other meteorological parameters. Currently temperature is the main concern, but as the climate continues to change, other weather factors may become equally important, therefore continued monitoring is essential.

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Table 1. Comparisons of measured vs. PTAA annual balance (R^2). (Period 1965–2012 used for Alaska glaciers; period 1953–2011 used for Austria glaciers.)

Glacier name	NET	ABL	ACC
Gulkana	0.51	0.58	0.01
Wolverine	0.57	0.18	0.44
Lemon Creek	0.20	n/a	n/a
Hintereisferner	0.47	n/a	n/a
Kesselwandferner	0.37	n/a	n/a
Vernagtferner	0.67	0.54	0.25

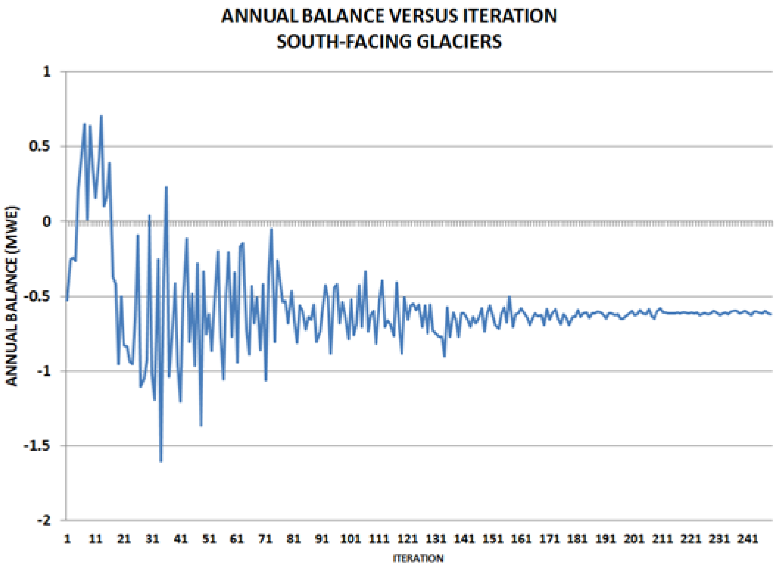

Figure 1. Mean annual balance for the 1951–2012 period for south-facing glaciers of the Wrangell Range, Alaska vs. iteration number. The first fifteen balances are calculated from pre-set coefficients, the remaining 250 are determined by the simplex by minimizing the calibration error.

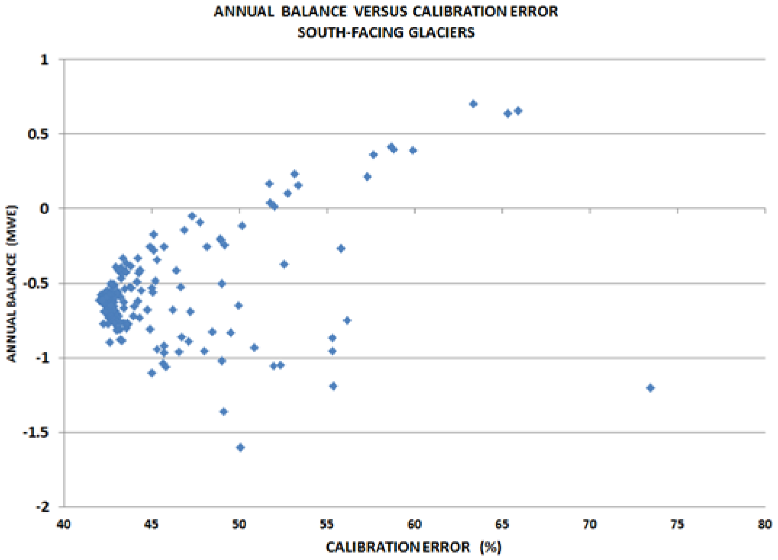

Figure 2. Mean annual balance of the south-facing glaciers of the Wrangell Range vs. calibration error. The calibration error is a minimum (about 43 %) when the mean annual balance is approximately −0.6 m w.e.

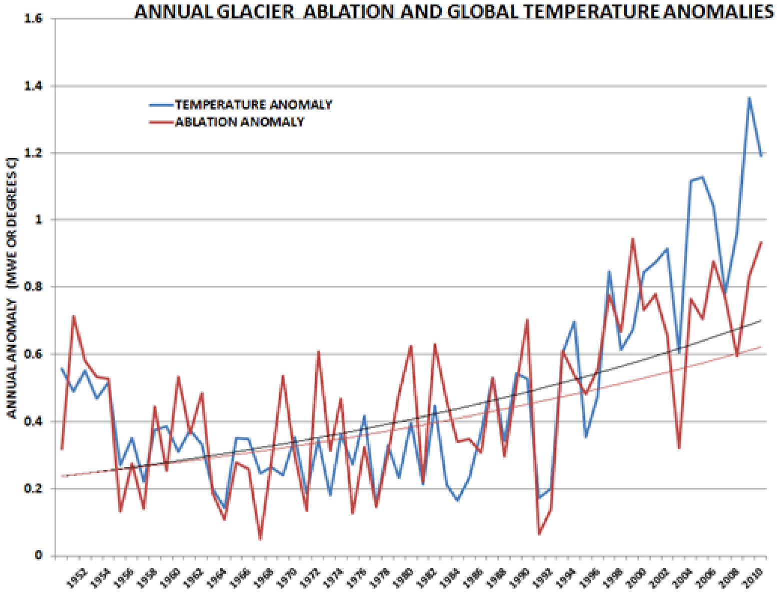

Figure 3. Annual ablation anomalies for the Wrangell Range glaciers and annual temperature anomalies derived from 7000 weather stations in the Northern Hemisphere. The R^2 for a regression fit of these variables is 0.61 (see Fig. 2). The similar patterns of each variable and fitted trend lines suggest that both global temperatures and glacier ablation are controlled by a common forcing mechanism, which likely is the rising concentration of atmospheric carbon dioxide but a direct cause is unknown.

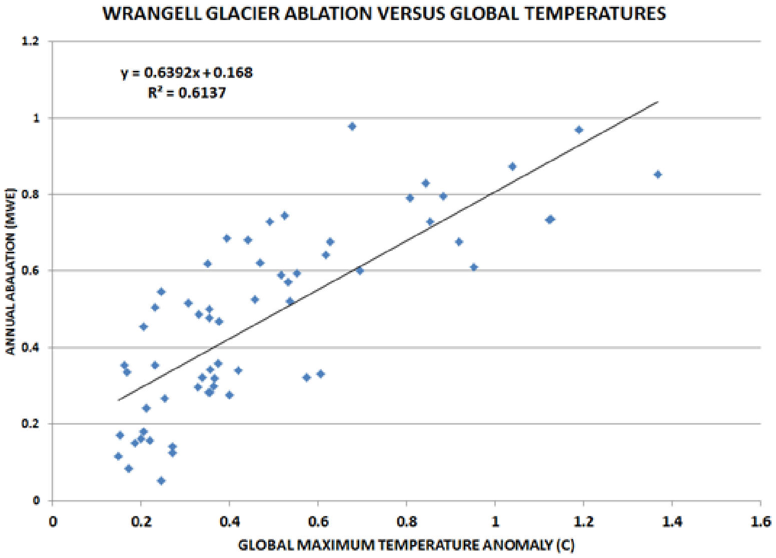

Figure 4. Annual ablation of Wrangell Range glaciers in Alaska vs. global maximum temperature anomalies (the same data as shown in Fig. 3). Glacier ablation is dependent on global temperature anomalies by: DA = 0.6(DT) + 0.17, where DA = ablation anomaly, DT = temperature anomaly. The correlation coefficient is +0.78.