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ORIGINAL ARTICLE

Multivariate models for predicting glacier termini

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Abstract

Concerns over the rapid retreat rates of mountain glaciers have been rising as global temperatures have continued to increase. The extent of variation in the retreat of mountain glaciers can provide information about changes to different climatic conditions. Assessing the retreat rates of glaciers is crucial to assess the continuing existence of mountain glaciers and the ramifications of those retreats on water security for human societies. Therefore, mathematical and statistical models for the quantification of glacier dynamics in response to climate change are in high demand. In this research, we propose a multivariate regression model that estimates glacier change and predicts the location of glacier terminus over time, based on observed climate factors. The proposed method is applied to temporal sequences of ground observations for a number of glaciers around the globe. This model can potentially be used for monitoring glacier systems using climatic factors.

Keywords Climate change · Mountain glaciers · Statistical analysis · Regression · Multivariate models · Correlation · Prediction · Terminus location · Climate factors

Introduction

In our previous work (Kachouie et al. 2013, 2015) we proposed a statistical method for estimating the location of a glacier terminus over time, from a sequence of Landsat multispectral satellite images, by identifying an inflection point in the glacier's path intensity profile. A new processed band (NDTSI) was introduced using B62 and NDSI for glacier studies via remote sensing that provides a better estimation than any individual Landsat spectral band. A constrained bandwidth selection method using local polynomial regression was also introduced for the detection of glacier terminus. Here we propose a model for predicting the glacier terminus location over time based on observed climatic factors. This is achieved by applying multivariate regression to the temporal sequence of observed terminus locations using climatic factors.

The definition of climate change varies from any change in climate over time (Solomon et al. 2007) to changes in climate that result from human activity (UNFCCC 1995). Climate change is used synonymously with global warming, referring to the observed rise in global surface air temperatures during the past century (Hansen et al. 2010). In their most recent and Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), a body of work by thousands of scientists worldwide concluded that "Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems" (Pachauri et al. 2014). These impacts include global sea-level rise; ocean acidification; shrinking glaciers; changes to hydrologic cycles; smaller crop yields; more heat waves, droughts, and floods; and numerous other changes to natural and biological

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systems, including the extinction of some species (Pachauri et al. 2014).

The present research focuses on the impacts of a changing climate on mountain glaciers. Glacial ice covers over 15 million km^2 across the globe, with 1% of that area being contained in mountains (US NSIDC 2017). Mountain glaciers exist as massive ice sheets in locations where summer temperatures do not melt off snow that accumulated in past winters. Under the current climate conditions, mountain glaciers are found on every continent except Australia.

Because of their global ubiquity, mountain glaciers provide excellent evidence of climate change both regionally and globally (Owen et al. 2009). Glaciers are particularly sensitive to changes in temperature and precipitation, with their end point, or terminus, marking the line where climatic conditions no longer support glacial growth. This makes glaciers excellent probes of climate change (Haeberli and Beniston 1998), and observing glacial mass balance on decadal timescales gives clear insight into long-term climate trends.

Globally, glaciers began a general retreat after the Little Ice Age maximum, around 1600 (Oerlemans 2005), and continued to retreat until global temperatures cooled slightly during the 1940s through the 1970s. Glacial advances were observed in several regions of the world during these decades of cooling (Roer et al. 2008). However, since the 1980s glacial retreat has been accelerating (Roer et al. 2008; Dyurgerov and Meier 2000; Zemp et al. 2009).

Today, glacial retreat is documented in all regions of the world where glaciers exist: tropical Africa (Cullen et al. 2006); temperate areas such as New Zealand (Hoelzle et al. 2007), the USA (Lillquist and Walker 2006); the European Alps (Haeberli et al. 2007); the Himalayas (Agrawal 2013); subarctic regions, including Scandinavia (Andreassen et al. 2008; Nesje et al. 2008; Engeset et al. 2000); Alaska (Arendt et al. 2002); Canada (Gardner et al. 2011); and the Antarctic (Allison et al. 2009; Van Den Broeke et al. 2011). Two extensive reviews of worldwide changes to glaciers since the Little Ice Age maximum are given in Roer et al. (2008) and in Gardner et al. (2013). As a result of this melt, global sea levels are on the rise. Today's cryosphere stores the equivalent of a 65 m rise in sea level, and currently sea-level rise from glacier melt is roughly 1.5 mm per year (Jacob et al. 2012). Future projections of glacial melt suggest that almost a quarter of mountain glacial volume could disappear by 2100 (Radić and Hock 2011), with total ice loss contributing to a sea-level rise of around 30 cm (Bamber and Aspinall 2013) to half a meter (Pfeffer et al. 2008).

Despite this vast retreat, some glaciers have been observed to be stagnant or even advancing, while nearby glaciers have been observed to be retreating (Andreassen et al. 2008; Nesje et al. 2008). Because of the variation in the response of individual glaciers within a region with similar climatic conditions, particularly temperature and precipitation, it is important to consider shading, cloudiness, and wind-driven snow accumulation when determining how individual glaciers will respond to a changing climate (Owen et al. 2009).

Interestingly, changing weather patterns as a result of global warming can also explain glacial advance. Advances in the Karakoram Himalayas over the last two decades are perhaps a result of increased precipitation (Hewitt 2005). This same reasoning explains the advancement of some high elevation glaciers in the nearby Zanskar Himalayas (Kamp et al. 2011). The advancement of individual glaciers does not disprove the overwhelming evidence of a globally warming climate. Instead, it highlights that whether the global parameters, such as global temperature, can explain the behavior of glacier variations, at least for some glaciers, or local parameters, such as local temperature, can better explain glacial mass balance to model the behavior of individual glaciers.

In this study, we use regression models to study the correlation between the terminus location and climatic factors, including atmospheric CO_2 concentration, global temperature, and local temperature. In "Data and variable definition" section, we provide information about the five glaciers that we investigated in this study as well as the factors that we used to explain the changes in the terminus location. In "Methods" section, we discuss the regression models and analyze the significance of each climate factor on explaining terminus location. "Results" section gives the results of our analysis, and we discuss the implications of these results in "Discussion" section.

Data and variable definition

In this research, we study five glaciers around the world including the White Glacier in the northwest USA, the Baegisarjokull Glacier in northern Iceland, the Gorner Glacier in the Swiss Alps, the Zemu Glacier in the Himalayas, and the Franz Josef Glacier of New Zealand. The locations of these five glaciers (Fig. 1) provide a global coverage to interpret glacial length change, both individually and globally. In the proposed regression model, terminus location is the response variable (S) and three predictors are used for predicting the glacier's terminus location, including spatiotemporal (globally annually) average temperature (T_g), local temporal (annually) average temperature (T_l), and temporal (annually) average atmospheric carbon dioxide concentration (CO_2).

For each glacier, the terminus location is measured in meters from a previous reference point. The terminus change is then calculated using each new measurement, and by summing them, we will have a time series of total terminus

Fig. 1 Locations of the five glaciers. Map data: Google (Google Maps 2017), NASA, and TerraMetrics. Created using Quantum GIS (Quantum GIS Development Team 2015)

Table 1 Ground measurement data

Glacier index	Glacier	Temporal domain	Number of terminus measurements
1	White, USA	1960–1977	11
2	Baegisarjokull, ICE	1977–2007	6
3	Gorner, SWI	1883–2005	111
4	Zemu, IND	1981–1987	7
5	Franz Josef, NZ	1894–2009	51

change. There is no comprehensive dataset available with several decades of annual measurements of glacier terminus locations. Rather, the available dataset contains infrequent measurements of terminus location, with considerable temporal gaps (in year). For example, there is a 5-year measurement gap for a glacier with no measurement from 1959 to 1964. Available terminus location measurements for the glaciers in this study are summarized in Table 1, where we use an index number (from 1 to 5) for each glacier. The temporal domain displays the time from the first to the last measurement. The number of measurements is different for these five glaciers, and as we can see in Table 1, there are a considerably larger number of measurements for Glaciers 3 and 5.

Spatiotemporal average temperature T_g is sourced from the NASA Goddard Institute for Space Studies (Hansen et al. 2010) from 1880 to 2013. Temporal average temperature T_l is taken from the closest station to each glacier. The coordinates of each glacier along with the location and the elevation of the local temperature station(s) are summarized in Table 2 for each glacier.

Each glacier has one temperature recording station within a reasonable distance (local) of the glacier, except Glacier 1, with three local stations that can be used for obtaining temporal local average temperature (T_l). Therefore, T_l is computed as weighted average of these three stations based on their distances to the glacier. Both T_g and T_l are temperature anomalies in degrees of Celsius with a 30-year average reference (1951 through 1980).

CO_2 was sourced from the Law Dome Ice Core (Etheridge et al. 1996) from 1880 to 1958 and from the Scripps Institute at Mauna Loa from 1959 to 2013. Both sources provide CO_2 in parts per million by volume (ppmv). Since each CO_2 data sources partially cover the time span of the terminus location measurements, both sources are needed to provide a complete temporal coverage of the ground measurement dates for all five glaciers. We have shown in Results section that these two individual CO_2 datasets are well correlated to be combined in a composite CO_2 dataset.

Methods

In this research multivariate models are employed to study mountain glacier terminus variations. First, we study the relation between glacier terminus location (S) as response variable and one of the predictors (CO_2, T_g, or T_l) in a simple regression model:

Table 2 The location of each glacier, the location and elevation of the local temperature stations used to determine T_l for each glacier

Glacier index	Location	Closest temperature station	Station distance from glacier	Station elevation (m)
1	47.8 N, 123.7 W	Forks, USA	50 km W	91
		Port Angeles, USA	40 km NE	17
		Cushman Powerhouse, USA	58 km SE	7
2	65.6 N, 18.4 W	Akureyri, ICE	18 km E	27
3	46.0 N, 7.8 E	Geneva, SWI	133 km W	375
4	27.8 N, 88.3 E	Pagri, CHN	80 km E	4300
5	43.5 S, 170.2 E	Hokitika Aero, NZ	110 km NE	39

Simple Linear Regression Model $\quad Y = \beta_0 + \beta_1 X_1 + \varepsilon$ (1)

where Y is the response variable (S), X_1 is the predictor (CO_2, T_g, or T_l), and ε is observational error. Simple linear regression models in this study are:

$$\begin{aligned} &\text{Model 1} \quad S = \beta_0 + \beta_1 CO_2 + \varepsilon, \\ &\text{Model 2} \quad S = \beta_0 + \beta_1 T_g + \varepsilon, \\ &\text{Model 3} \quad S = \beta_0 + \beta_1 T_l + \varepsilon. \end{aligned} \tag{2}$$

In the next step, we use multivariate regression models to investigate whether models consisting of temperature and CO_2 can better explain the observed variations in the glacier terminus position:

Multivariate Regression Model

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots + \beta_k X_k + \varepsilon \tag{3}$$

The multivariate model in Eq. 3 is customized to the following two models (for each glacier):

$$\begin{aligned} &\text{Model 4} \quad S = \beta_0 + \beta_1 CO_2 + \beta_2 T_g + \varepsilon, \\ &\text{Model 5} \quad S = \beta_0 + \beta_1 CO_2 + \beta_2 T_l + \varepsilon. \end{aligned} \tag{4}$$

A multivariate model investigating T_g and T_l was not included because they are the same parameter (temperature) differing only in spatial scale. We added an interaction term to the multivariate model in Eq. 3 to further study the interaction between temperature and CO_2:

Multivariate Regression Model with Interaction

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 + \varepsilon \tag{5}$$

The interaction term was used to examine whether the effect of temperature (T_g or T_l) on glacier location (S) depends on the CO_2 level. These interactions provide two additional models with interaction terms:

$$\begin{aligned} &\text{Model 6} \quad S = \beta_0 + \beta_1 CO_2 + \beta_2 T_g + \beta_3 CO_2 T_g + \varepsilon, \\ &\text{Model 7} \quad S = \beta_0 + \beta_1 CO_2 + \beta_2 T_l + \beta_3 CO_2 T_l + \varepsilon. \end{aligned} \tag{6}$$

As will be shown in Results section, short-time observations of interannual variability in local and global temperature may not reveal the long-term trends. To account for this and remove the short-term variability, additional models were included with 7-year moving averages of temperature (local or global). A 7-year moving average is selected by considering climate factors such as the El Niño–Southern Oscillation Index, which is a phenomenon with global weather impacts with a period of 2–7 years (MacMynowski and Tziperman 2008). Previous models (Model 2–Model 7) are repeated using the smoothed temperature variables, $\bar{T}_g$ or $\bar{T}_l$, resulting in six additional models:

$$\begin{aligned} &\text{Model 8} \quad S = \beta_0 + \beta_1 \bar{T}_g + \varepsilon, \\ &\text{Model 9} \quad S = \beta_0 + \beta_1 \bar{T}_l + \varepsilon, \\ &\text{Model 10} \quad S = \beta_0 + \beta_1 CO_2 + \beta_2 \bar{T}_g + \varepsilon, \\ &\text{Model 11} \quad S = \beta_0 + \beta_1 CO_2 + \beta_2 \bar{T}_l + \varepsilon, \\ &\text{Model 12} \quad S = \beta_0 + \beta_1 CO_2 + \beta_2 \bar{T}_g + \beta_3 CO_2 \bar{T}_g + \varepsilon, \\ &\text{Model 13} \quad S = \beta_0 + \beta_1 CO_2 + \beta_2 \bar{T}_l + \beta_3 CO_2 \bar{T}_l + \varepsilon. \end{aligned} \tag{7}$$

These models are summarized in Tab. 3 and were coded using the R Statistics Package (R Core Team 2013).

We have also estimated the correlations between the predictors using the following simple regression models:

$$\begin{aligned} &\text{Correlation Model 1} \quad T_g = \beta_0 + \beta_1 CO_2 + \varepsilon, \\ &\text{Correlation Model 2} \quad T_l = \beta_0 + \beta_1 CO_2 + \varepsilon, \\ &\text{Correlation Model 3} \quad T_l = \beta_0 + \beta_1 T_g + \varepsilon. \end{aligned} \tag{8}$$

Results

Univariate and multivariate regression models introduced in method section (Table 3) are used to model variations in the glacier terminus location based on CO_2, T_g, and T_l,. We applied these models to the ground measurements of terminus locations for the aforementioned five glaciers in the Data Section, including the Gorner Glacier in Switzerland,

Table 3 The 13 models used to explain the variation in S, hereafter referred to by model number

Model number	Predictor(s)	Model number	Predictor(s)
1	CO_2	8	$\bar{T}_g$
2	T_g	9	$\bar{T}_l$
3	T_l	10	$CO_2 + \bar{T}_g$
4	$CO_2 + T_g$	11	$CO_2 + \bar{T}_l$
5	$CO_2 + T_l$	12	$CO_2 + \bar{T}_g + (CO_2 \times \bar{T}_g)$
6	$CO_2 + T_g + (CO_2 \times T_g)$	13	$CO_2 + \bar{T}_l + (CO_2 \times \bar{T}_l)$
7	$CO_2 + T_l + (CO_2 \times T_l)$		

Franz Josef in New Zealand, Zemu in India, Baegisarjokull in Iceland, and the White Glacier in the northwestern region of the USA. Glacier terminus variations along with the CO_2 levels and temperature patterns over time (between 1880 and 2000) are shown in Fig. 2.

In Fig. 2, we can observe the same trend for CO_2 concentration and global temperature during the period of 1880–2000, where they both appear to be steadily increasing. The glacier lengths for all depicted glaciers, except the Franz Josef Glacier (Fig. 3), have been decreasing during the entire interval.

The Franz Josef Glacier's terminus location has been advancing for a certain period, while CO_2 concentrations and global temperature have been increasing (Figs. 2 and 4). Increased snowfalls in the region during this period may account for this anomalous behavior. Regression lines are added to better observe this trend. Variations in glacier terminus associated with variations in carbon dioxide, global, or local temperature are summarized in Table 4 of Electronic Supplementary for univariate regression models.

Regression model 1: glacier terminus location variation versus carbon dioxide concentrations

Terminus location variations modeled using regression model 1 (fitted planes) are depicted in Fig. 4 for five glaciers. The R^2, reported in Table 4 of Electronic Supplementary, is between 0.42 and 0.98 for these five glaciers. However, it seems that Franz Joseph Glacier (Fig. 4b) with the lowest R^2 among them has a nonlinear trend. Regardless of observing a consistent decreasing trend of glacier terminus location, or an irregular trends, with irregular advancements, the terminus location at the end of the studied period is receded in

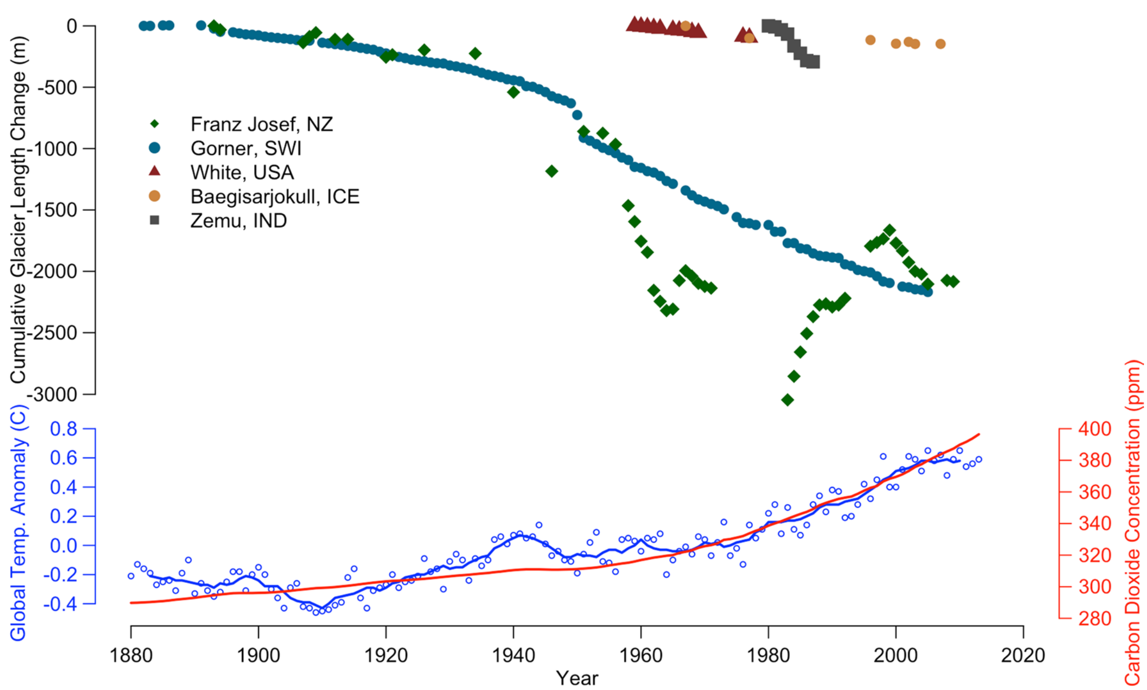

Fig. 2 Top: cumulative glacier length variations versus year: Franz Joseph (green), Gorner Glacier (blue), White Glacier (brown), Baegisarjokull Glacier (yellow), and Zemu Glacier (gray). Bottom: global temperature (blue circle), smoothed pattern (solid blue), and CO_2 (solid red)

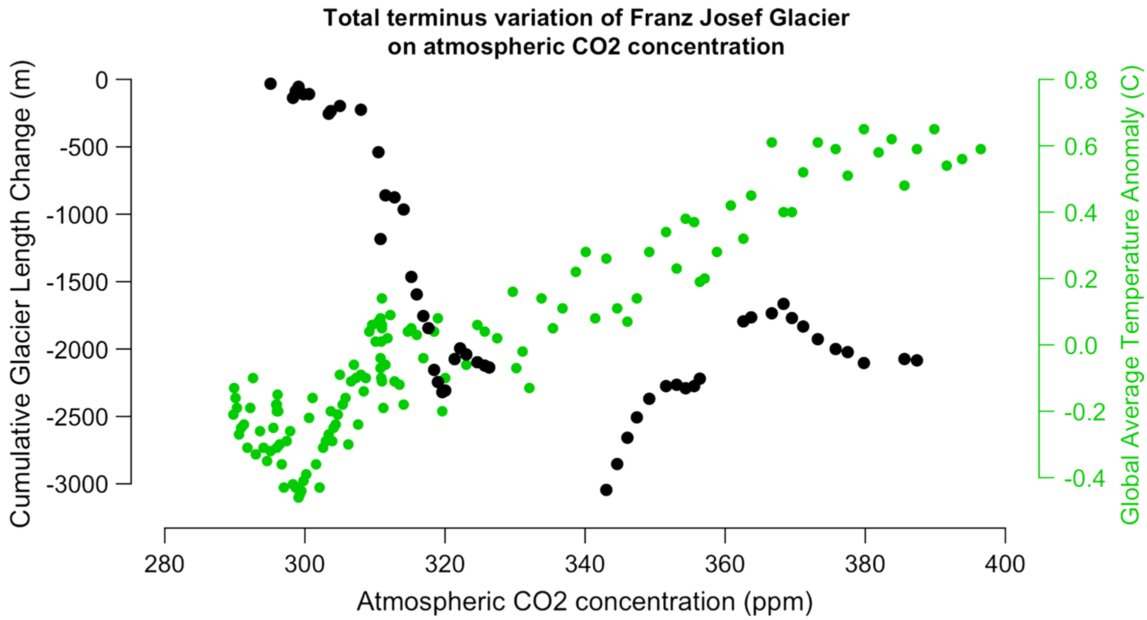

Fig. 3 Terminus location variation for the Franz Joseph Glacier. Terminus variation versus CO_2 concentration (black) and global average temperature versus CO_2 concentration (green)

comparison with its location in the beginning of the studied time period for all five glaciers.

Figure 4a, b shows a trend for Franz Josef and Goner Glaciers with a period of glacier receding followed by some advances in the glacier terminus location. Figure 4c–e shows a decrease in glacier length over time, except a slight length increase for the Baegisarjokull Glacier toward the end of studied period, for White, Baegisarjokull, and Zemu Glaciers, respectively, as atmospheric carbon dioxide concentration increases in the investigated time period. There are 111 and 51 glacier terminus measurements for Gorner and Franz Josef Glaciers; however, notice that there are fewer ground measurements available for White, Baegisarjokull, and Zemu Glaciers than for the other glaciers (Table 1).

Regression model 2: glacier terminus location variation versus global temperature

All but the Zemu Glacier with R^2 value of 0.017 (Fig. 5e of Electronic Supplementary) indicate a decreasing trend of the glacier length associated with increasing global temperature (Fig. 5 in Electronic Supplementary file). Gorner and Baegisarjokull Glaciers (Fig. 5a, d of Electronic Supplementary) with R^2 values of 0.74 and 0.68 show strong correlations between glacier terminus location and global temperature. Franz Josef Glacier (Fig. 5b of Electronic Supplementary) with R^2 value of 0.39 demonstrates moderate correlation, while no correlation between glacier terminus location, and global temperature was observed for the White and Zemu Glaciers using this regression model.

Regression model 3: glacier terminus location variation versus local temperature

It can be seen in Table 4 of Electronic Supplementary, except for Baegisarjokull Glacier, the local temperature cannot predict the glacier terminus variation with R^2 values ranging from 0.11 to 0.28. The univariate models 1, 2, and 3, can be summarized as follows. Global temperature can moderately predict the glacier terminus variation for Glaciers 2 and 3. However, CO_2 highly explains terminus location for Glaciers 1–4 including the White, Baegisarjokull, Gorner, and Zemu Glaciers with R^2 values ranging from 0.80 to 0.98. Neither global temperature nor CO_2 can predict much of the variation in Franz Josef terminus location (R^2 values of about 0.4). Surprisingly, local temperature does not perform better than the global temperature to explain the terminus location variations. Overall, carbon dioxide concentration is the best single predictor among the three predictors to explain the variation in glacier terminus.

Regression models 4 and 5: multivariate models for glacier terminus location variation

In order to verify whether a combination of the predictors could better explain the variation in glacier terminus, we applied multivariate models with CO_2 and temperature as predictors. The results for model 4 (with global temperature and CO_2 as predictors) and model 5 (with local temperature and CO_2 as predictors) are shown in Table 5 of Electronic Supplementary. Both models can explain the glacier terminus

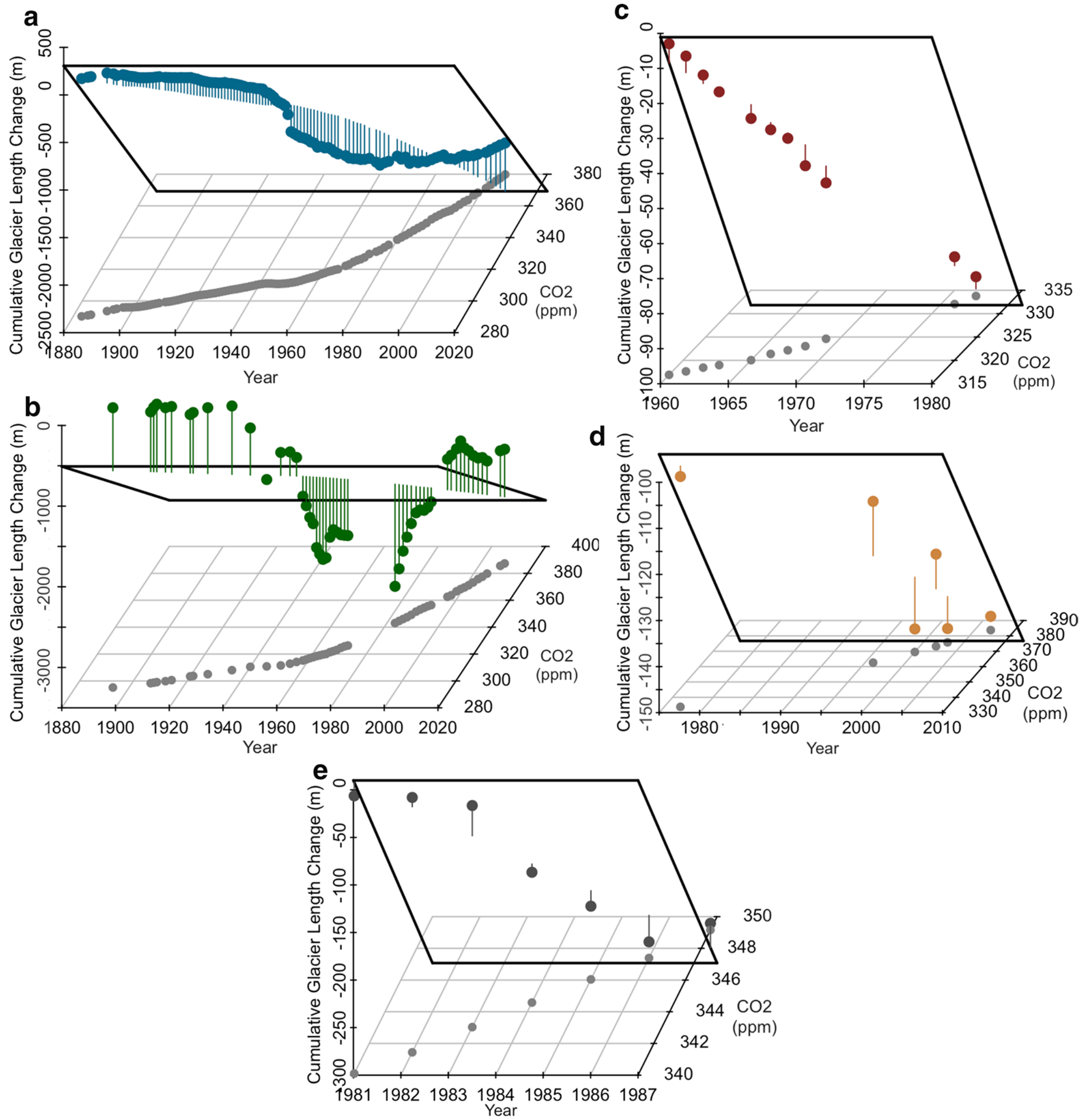

Fig. 4 Cumulative glacier terminus length changes (z-axis) over a period of years (x-axis) with atmospheric carbon dioxide concentration (y-axis): **a** Gorner Glacier, **b** Franz Josef Glacier, **c** White Glacier, **d** Baegisarjokull Glacier, and **e** Zemu Glacier. The estimated regression plane is superimposed to show the trend of data during the given period. The cumulative glacier terminus length change is also projected onto the x–y-axis to show the two-dimensional (2D) relationship between the year and the atmospheric carbon dioxide concentration (ppm)

location variation in four of the glaciers with R^2 ranging from 0.80 to 0.98. These models could also somewhat explain the glacier terminus location variation for Franz Josef Glacier with R^2 value of 0.42 in model 4 and 0.47 in model 5.

Overall, multivariate models 4 and 5 provide just slight improvements in comparison with models 1–3. The results show that combining the temperature (global or local) with CO_2 in a multivariate model does not considerably help to explain the remaining variation in glacier terminus location for Franz Josef (max. R^2 of 0.47) and Baegisarjokull (max. R^2 of 0.82), which also implicitly highlights the correlation between CO_2 concentrations and the temperature.

Regression models 6 and 7: multivariate models with interaction for glacier terminus location variation

Next, to further investigate the combined influence of two predictors and their interaction on glacier terminus variation, we use models 6 and 7 (multivariate regression models with interaction). There were slight improvements in R^2 (Table 6 of Electronic Supplementary) for four (out of 5) glaciers in comparison with previous models. However, the R^2 values of 0.78 (in model 6) and 0.61 (in model 7) for Franz Josef show much better prediction of variations in glacier terminus for this glacier by these two models. Surprisingly, in contrast to our expectations, replacing global temperature with local temperature does not improve R^2 for these glaciers, and even for Franz Josef, the predictions using global temperature are better than the predictions obtained by local temperature in the interaction model.

Regression models 8 and 9: glacier terminus location variation versus smoothed temperature

Model 8 is a simple linear regression to predict glacier terminus location variation using smoothed global temperature, where global annual temperature is smoothed using a 7-year moving average. R^2 values for model 8 are depicted in Table 7 of Electronic Supplementary and range from 0.13 to 0.83 for the five studied glaciers. It can be seen that this model can explain more than 80% of the variation of glacier terminus location for three glaciers. Although model 8 (using smoothed global temperature) only explained 13% and 43% of the terminus location variations for the White and Franz Josef Glaciers, respectively, it still performed better than model 1 (using global temperature without smoothing).

Model 9 is similar to model 2 in that the local temperature was replaced with smoothed local temperature using a 7-year moving average. Figure 6 of Electronic Supplementary shows glacier length variations against the smoothed 7-year average local temperature over time. The common receding trend of glacier length can be observed in Fig. 6 (specifically in Fig. 6a, b) in Electronic Supplementary file similar to what we observed in Figs. 4 and 5 of Electronic Supplementary.

Glaciers in Fig. 6c, d of Electronic Supplementary have less steep declines in comparison with those in Fig. 6a, b of Electronic Supplementary. Fewer available ground measurements could potentially justify these moderate slopes. The R^2 values range from 0.01 to 0.86 (Table 7 of Electronic Supplementary). This model can explain 65% and 86% of the variation in terminus location in the Franz Josef (Fig. 6b of Electronic Supplementary) and the Baegisarjokull Glacier (Fig. 6d of Electronic Supplementary), respectively, which shows a substantial improvement in comparison with model 2 (with 40% and 68% of the explained variation) for these two glaciers (Table 4 of Electronic Supplementary). Despite having only a handful of ground measurements for the Baegisarjokull Glacier, the model with the 7-year smoothed local temperature anomaly noticeably predicted the variation in terminus location. However, for Zemu Glacier with about the same number of ground measurements, the model did not predict the glacier terminus location variations, with the R^2 value close to zero and negative adjusted R^2 value due to small sample size (number of measurements).

Regression models 10 and 11: multivariate models using smoothed temperature

Temperature in the multivariate regression models 8 and 9 is replaced with smoothed temperature in models 10 and 11. The R^2 values for model 10 using smoothed global temperature and CO_2 as predictors, are depicted in Table 8 of Electronic Supplementary and range from 0.43 to 0.99 for the five studied glaciers. The R^2 values are substantially improved for all but Baegisarjokull Glacier in comparison with model 8. The R^2 values for model 11 using smoothed local temperature and CO_2 as predictors are also depicted in Table 8 of Electronic Supplementary and range from 0.65 to 0.99 for the five studied glaciers. Model 11 demonstrates considerable improvement regarding predictions of the variation of glacier terminus location by smoothed temperature and CO_2. The R^2 value of model 9 for White Glacier is 0.34 versus 0.995 of model 11. The R^2 value of model 9 for Gorner Glacier is 0.39 versus 0.93 of model 11. For Zemu Glacier, these values are 0.01 and 0.97 for models 9 and 11, respectively.

Regression models 12 and 13: multivariate models with interaction using smoothed temperature

Similar to models 6 and 7, multivariate models with interactions are applied to these five glaciers to investigate the combined influence of two predictors and their interaction on glacier terminus variation. However, in contrast with models 6 and 7, smoothed temperature is used in models 12 and 13 in place of temperature itself. The R^2 values are depicted in Table 9 of Electronic Supplementary, and as we can observe, the R^2 values of models 6 (global temperature and CO_2 as predictors) and 12 (smoothed global temperature and CO_2) are almost the same. However, prediction of glacier terminus variations is improved by 5% and 10% for Franz Josef and Baegisarjokull Glaciers, respectively, by model 12 in comparison with model 6. Similarly, the R^2 values of models 7 (local temperature and CO_2 as predictors) and 13 (smoothed local temperature and CO_2) are almost the same except for Franz Josef Glacier with 17% improvement in R^2 value by model 13.

Discussion

Mountain glaciers have been responding to recent increases in global temperature. The mountain glacier variations can represent the extent of changes in climate factors. Measuring the variation rate of glaciers is vital due to its impact on water security. In this research, we studied several models to predict the glacier terminus location based on two important climatic factors, including temperature (global/local) and CO_2. Simple regression, multivariate regression, and multivariate regression models with interactions were designed for locating the glacier terminal point based on these predictors (temperature and CO_2). Annual global temperature, annual local temperature, and 7-year moving average of each variable were investigated in our study. Seven-year moving averages were selected to remove the short-term variability introduced by some other climatic factors, such as the El Niño–Southern Oscillation Index. This index has a global climate impact reoccurring with a period of 2–7 years.

As a single predictor, carbon dioxide concentration (CO_2) could explain the terminus location variation much better than either global or local changes in the temperature for all five glaciers. Specifically, global temperature could explain less than 2% of the variations in the glacier terminus location for the Zemu and White Glaciers. Local temperature performed better than global temperature to predict glacier terminus location for these two glaciers, by explaining less than 13% of the variation. In contrast, CO_2 explained more than 96% of the variation in terminus location for Zemu and White Glaciers.

We should point out that the change in CO_2 is not the main cause of glacier terminus change; rather, it shows that there is a strong correlation between terminus location and CO_2 concentration such that CO_2 can explain the variation in terminus location better than global or local temperature. Nevertheless, temperature could be the main cause of the variation in terminus location.

Despite our expectation that regional variables could perform better to predict the glacier terminus location, the multivariate regression with interactions, using smoothed global temperature and CO_2 as predictors (model 12), performed better than the other models in predicting the terminus location. The multivariate regression with interaction using smoothed local temperature and CO_2 (model 13) performed almost the same (within 1% difference) for three of the glaciers. However, smoothed global temperature in the multivariate model with interaction improved the prediction of glacier terminus location by 6% in comparison with smoothed local temperature for Baegisarjokull in Iceland and Franz Josef in New Zeeland. This could perhaps be explained by the fact that Zemu and White Glaciers are in vicinity of Arctic/Antarctic climate, which is highly sensitive to global variations of temperature. Moreover, the glacier melt in Arctic/Antarctic is mainly influenced by sea temperatures, rather than air temperature. This can perhaps explain why the local (air) temperature does not explain the terminus location variations as well for Baegisarjokull in Iceland and Franz Josef in New Zealand.

As monitoring of glacier systems using climate factors is crucial for water security, future work should incorporate more climate factors, including neighboring sea surface temperature, to investigate their impact on mountain glacier variations. The proposed model can be effectively used for predicting the advance and retreat of other mountain glaciers around the globe.

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