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Simulation of a tidewater glacier evolution in Marian Cove, King George Island, Antarctica

J. Lee*
Y. K. Jin
J. K. Hong
Korea Polar Research Institute, Incheon, Korea
Korea University of Science and Technology, Daejeon, Korea
H. J. Yoo *Korea Power Engineering Company, INC*
H. Shon *Pai Chai University, Daejeon, Korea*

ABSTRACT: **Glacier changes in Marian Cove, King George Island (KGI) were investigated on the basis of observed and modeled data. Air temperature observations for the past 51 years recorded at the Russian Bellingshausen Station (BS) and aerial photographs provided adequate proofs of glacier retreat and regional warming. One-dimensional numerical simulations with yearly variant mass balance were performed to evaluate the glacier advance and retreat history. Then the models were validated by observed data. The results indicate that the mass balance of 0.6 m a^{-1} is a threshold point determining glacier advance or retreat in Marian Cove. The glacier changes are mainly affected by the ice thickness at the terminus and the local mass balance. The mass balance also affects glacier displacement in subsequent years. Marian Cove is probably ice-free by 2060 under condition of present warming trend.**

Key words: tidewater glacier simulation, regional warming, Antarctica, King George Island, calving

1. INTRODUCTION

Tidewater glaciers, which are considered as grounded calving glaciers discharged into oceans, are more important than other types of glaciers because such maritime glaciers are more sensitive than land glacier to the climate changes (Nick et al., 2006). Climate variation has been known as a cause to change length of glaciers (Oerlemans, 1994; 1997). However, there are possibly others causes to explain rapid changes in front positions of the tidewater glaciers other than climate changes (Meier and Post, 1987; Naruse and Skvarca, 2000; Vieli et al., 2001). For example, Lange Glacier on KGI has retreated over 35 years in accordance with a regional climate change, while an unnamed adjacent glacier advanced over the same period (Macheret and Moskalevsky 1999). This suggests that glacial retreat and advance are controlled by some other factors such as basal topography and calving rate of the glaciers terminus (Van der Veen, 1997; Vieli et al., 2001).

Recently, many sophisticated models have been developed to explain dynamical behavior of tidewater glacier related to climate changes and calving rates. The models do not accurately simulate tidewater glaciers because most of time variant parameters such as surface mass balance are assumed to be constant over time (Vieli et al., 2001; Nick et al., 2006). In this study, we will show the evolution of the tidewater glacier by numerical simulations. We use more realistic inputs of yearly variant surface mass balance. In order to validate our simulations, we compare the results with coastline data which are obtained by aerial photographs and satellite images. Finally, we estimate the variation of glacier front over the last 51 years, discuss the effects of mass balance and basal topography on the glacial fluctuation, and predict future glacier changes.

2. STUDY AREA

KGI is the largest island of the South Shetland Islands. It is located close to the northern tip of the Antarctic Peninsula (Fig. 1). The island is dominated by a huge ice cap. More than 91.7% of the island is glaciated (Simões et al., 1999). The study area is the tidewater glacier in Marian Cove. Marian Cove is located in Maxwell Bay on the southwest side of KGI. A glacier in Marian Cove is a grounded tidewater glacier and ends with a 1.2-km-wide and 2.8-km-long calving front in Marian Cove.

The region has a typical maritime climate, with little variation in air temperature through the year, frequent summer rain, high relative humidity, and constant cloud cover (Rakusa-Suszczewski et al., 1993). The field glaciological investigations were not executed until 2006. However, there have been several attempts to investigate showing glacier retreat with temperature variation (Park et al., 1998, Chung et al., 2004). The studies of the glacier in Marian Cove used aerial photographs to examine major changes in glacier front.

3. METHODS AND MATERIALS

3.1. Model Description

A model of a tidewater glacier dynamics must incorporate realistic description of calving and basal sliding, and must consider interactions between the calving process and

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*Corresponding author: joohan@kopri.re.kr

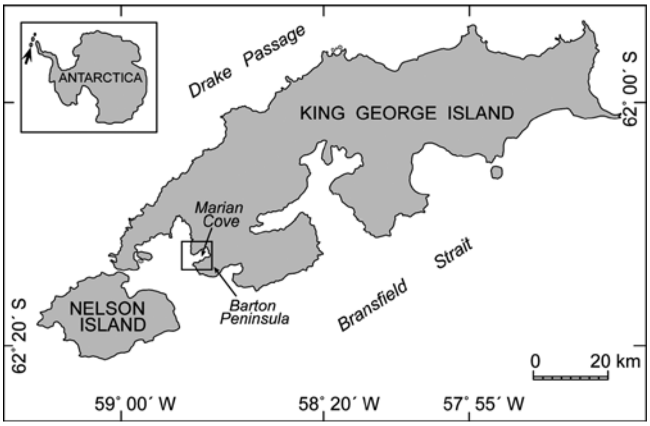

Fig. 1. Map of the study area in King George Island.

the dynamics of the entire glacier (Van der Veen, 1997). Here, a one-dimensional numerical ice flow model is used, which was introduced by Oerlemans (2001). This is time-dependent ice flow model that calculates the surface evolution and ice velocity along the flow line. A variation of glacier thickness with time is given by:

$$\frac{\partial H}{\partial t} = \frac{\partial (HU)}{\partial x} + B \qquad (1)$$

where t is time, x is distance along the flow line, H is the glacier thickness, B is surface mass balance, and U is ice sliding velocity. Normally, the sliding velocity (U) is the depth averaged velocity which is the result of stress and stress balance.

$$U = -\frac{2A}{n+2}\left[-\rho_i g H \frac{\partial h}{\partial x}\right]^n h^2 \qquad (2)$$

where n is a flow parameter (n=3 in this study), g is acceleration due to gravity (9.8 m s^{-2}), h is ice surface elevation, and A is an ice temperature dependent flow parameter, defined by an Arrhenius relation:

$$A = A_0\exp(-Q/RT) \qquad (3)$$

where A_0 is independent of temperature, R is the universal gas constant (8.31 J mol^{-1} K^{-1}), and Q is the activation energy for creep. Results of laboratory experiments on polycrystalline ice at temperatures below -10 °C give values of Q from 42 to 84 k J mol^{-1} with a mean of 60 k J mol^{-1} (Weertman, 1973).

In the equation, the surface mass balance (B) is an unknown parameter. Even if the simulation is based on the time-dependent finite-difference method (FDTD), most models set the mass balance to be constant or depend linearly on height (Oerlemans, 2001; Vieli et al., 2001; Nick and Oerlemans, 2006). In order to consider the effects of time variant temperature changes, we calculate the annual surface mass balance for the entire glacier using local air temperature variation. Generally, the surface mass balance is the result of the relationship between accumulation and ablation.

$$B = A_{acc} - A_{abl} \qquad (4)$$

Surface accumulation, A_{acc} (m a^{-1}), over the Antarctic ice sheet is parameterized as an exponential function of mean annual surface temperature T_{ann} (ºC) (Pattyn, 2006):

$$A_{acc} = 2.5 \times 2^{T_{ann}/10} \qquad (5)$$

Surface ablation, mainly related to surface and front melting, A_{abl} (ma^{-1}), is parameterized in an empirical form as a function of the mean summer temperature T_{sum} (ºC).

$$A_{abl} = \min(1.4 \times T_{sum};10)(T_{sum} \geq 0) = 0(T_{sum} < 0) \qquad (6)$$

Calving from tidewater glaciers is a dominant ablation mechanism. It allows much larger volumes of ice to be discharged in a short time than surface ablation (Van der Veen, 1996). Therefore, the model must consider calving in addition to glacier dynamics. Vieli et al. (2001) proposed a modified flotation criterion, where the frontal ice thickness above the floatation thickness is controlled by a small fraction q. In this case, the frontal ice thickness H_c is given by:

$$H_c = \frac{\rho_w}{\rho_i}(1+q)d \qquad (7)$$

where ρ_w and ρ_i are the density of water and glacier respectively, d is the water depth at the terminus and q is the small fraction parameter. This implies that if the frontal thickness of the glacier is below the critical thickness (H_c), the glacier is calved due to buoyancy. The glacier terminus position changes in response to the gap between the calving rate and the glacier flow velocity.

Equation (1) was solved on a grid along the flow line using an explicit FDTD method. There were 4,500 grid points along the flow line. The time steps and grid points satisfy the CFL (Courant-Friedrichs-Lewy) stability condition (Smith, 1978).

3.2. Model Input

3.2.1. Basal topography

In order to describe the basal topography, we used Marian Cove bathymetry data (Kim and Baek, 1995) along the flow line which is perpendicular to the crevasse direction and has a great length of glacier fluctuation (Fig. 2). Because bathymetry data are insufficient to describe all of the bed elevation along the flow line, we exponentially increased basal topography to upstream direction for the insufficient topography (Fig. 2). Total length of the glacier in 1956 was 4,500 m from the glacier summit. Maximum depth of the glacier bed was 136 m under the sea level.

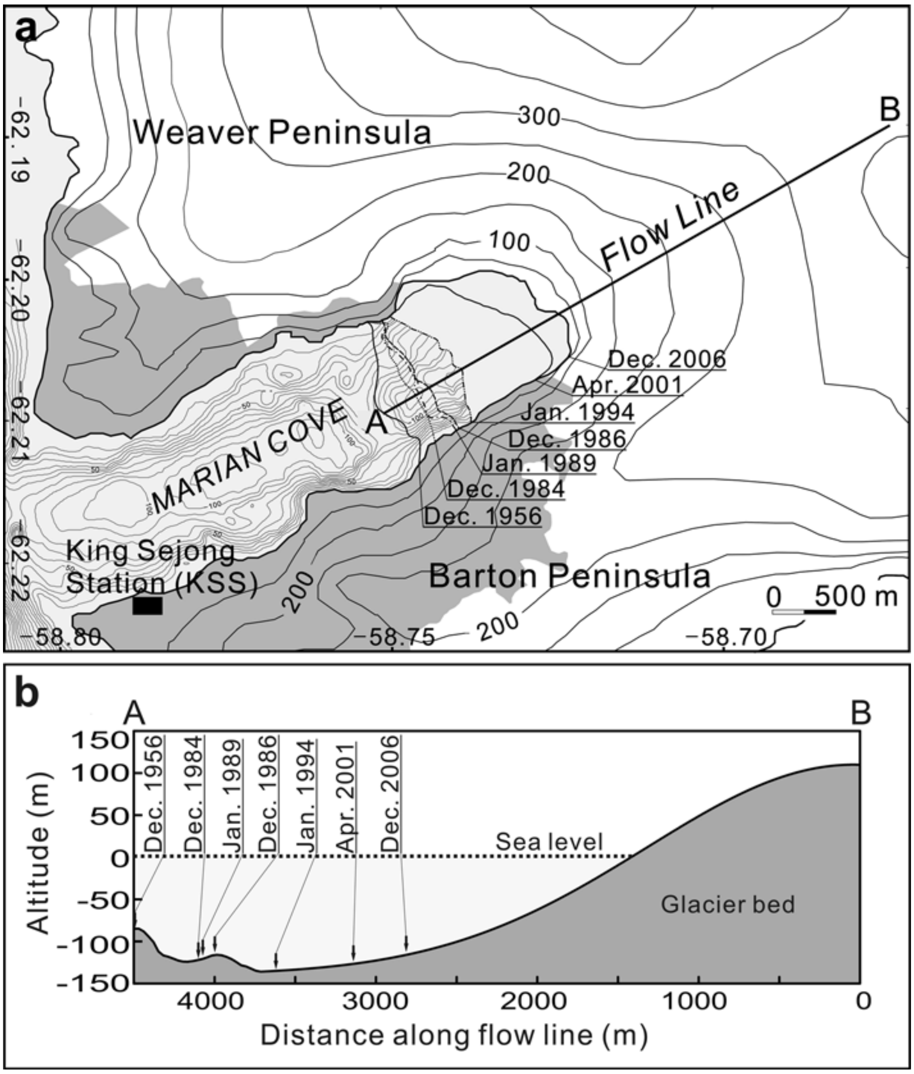

Fig. 2. Enlarged image showing the tidewater glacier in Marian Cove. (a) Observed glacier front position from 1956 to 2006 and (b) cross section of the basal topography along the flow line are illustrated. Flow line is 4,500 m length from A to B. 'A' denotes the glacier front in 1956 and 'B' is summit of the glacier. Positions of the glacier front between 1956 and 2006 are indicated by arrows in (b).

3.2.2. Temperature

The glacier is located near the King Sejong Station (KSS). Because the KSS was established in 1988, there are not enough air temperature data to cover the last 51 years. Earlier data are available from the BS. Two stations are apart 9.5 km from each other. The variation of temperature at the BS shows similar pattern to that of KSS (Fig. 3). Therefore we can adopt the temperature data from BS as a representative air temperature variation in Marian Cove. All of the air temperature data are available on the BAS (British Antarctic Survey) website.[1]

4. RESULTS AND DISCUSSION

4.1. Local Temperature

The mean annual air temperature at BS for last 51 years is -2.5 with a maximum of -0.7 ºC and minimum of -5.2 ºC. The annual mean air temperature record of BS shows a warming trend of 0.037 ºC a^{-1} which is equivalent to a warming of 1 ºC for 27 years. The mean summer temperature (December-February) is 1.1 ºC with a maximum of 2.0 ºC and minimum of -0.5 ºC. The summer air temperature increased at a slightly slower rate, 0.02 ºC a^{-1}, than the annual temperature (Fig. 3a).

The increased accumulation rate is attributed to climate warming (Hooke, 2005). Hence, an increased mean annual temperature implied an increased accumulation rate. The precipitation rate observed at KSS (Fig. 3b) increased during last 20 years (Cho and Park, 2007).

4.2. Observation of Glacier Front Positions

Sparse records of glacier front positions existed from 1956 to 2006 and a portion of the basal topography of the glacier was known (Fig. 2). Even though both data are insufficient to evaluate glacier behavior, these exist for a few tidewater glaciers (e.g., Cook et al., 2005). The com-

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[1] http://www.antarctica.ac.uk/met/gjma/

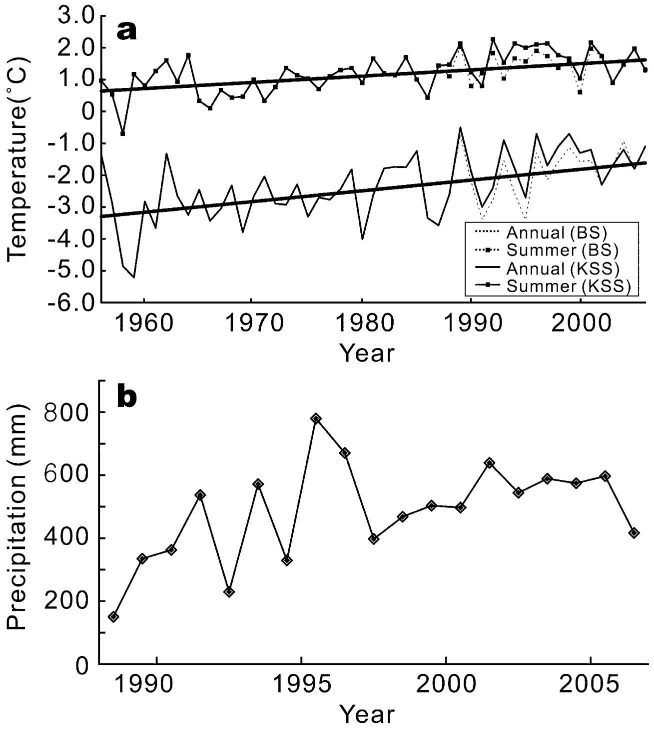

Fig. 3. The variations of air temperature and precipitation rate in KGI. (a) The annual mean air temperature record shows warming trend of 0.037 ºC a^{-1}. The increasing patterns of the temperature at the both KSS and BS are similar. (b) The precipitation rate observed at KSS increased during last 20 years.

Table 1. Recent glacier front changes of tidewater glacier along the flow line

Period (yrs)	Total changes (m)	Annual mean changes (m)
1956-1984 (29)	-350	-12.07
1985-1986 (2)	-150	-75
1987-1988 (2)	+66	+33
1989-1993 (5)	-369	-73.8
1994-2001 (8)	-621	-77.6
2002-2006 (6)	-276	-55.2
Total	-1,700	-33.3

parison of each aerial photograph of Marian Cove showed retreat and advance of the glacier front in the cove (Fig. 2). The glacier had been retreated 1,700 m along the flow line for the last 51 years (Table 1). Although the aerial photographs can hardly explain a periodic time series of the glacier, the patterns of glacier movement can be distinguished as two stages. First, the glacier front positions of 1956-1984 is nearly equilibrium state with only 437 m retreat while the glacier terminus entered into deeper water. Generally the rate of retreat increased as the glacier terminus entered into deeper water, resulting in a very high calving rate (Vieli et al., 2001). Second, the glacier experienced very fast variation including retreat (1985-2006) and advance (1988) with mean ice retreat rate of 67.4 m a^{-1}.

4.3. Simulation

Figure 4 shows snapshots of the glacier displacements. The time interval between each surface profile is two years. In order to validate the simulation, we compared the results of simulation to the observed data. Total retreat length of the glacier model is 1,650 m, which is a similar to that of the observation (1,700 m). Every location of the terminus is consistent with observations (Fig. 4). The distinctive result is the glacier advance from 1986 to 1988, which also appeared in the observations (Fig. 4). A small discrepancy can be found due to the insufficient data of basal topography. If the model parameters are not determined properly, the simulation results will not match with the observed data. Especially, without a proper mass balance it is impossible to predict how glaciers react to climatic change (Oerlemans, 2001). As a result, the simulation can be regarded as proper to describe the evolution of the glacier. Furthermore, the surface mass balance derived from empirical methods as the function of temperature is applicable for numerical simulation of tidewater glacier.

We experimented with three models to understand how the mass balance and basal topography affect movement of

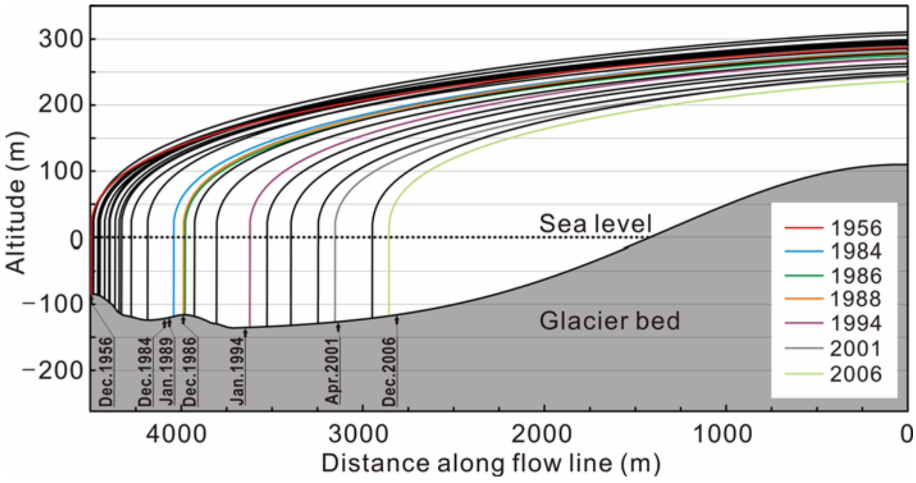

Fig. 4. The evolution of the glacier fronts along the flow line. The time interval between each surface is two years. Arrows indicate observed glacier front positions of corresponding years.

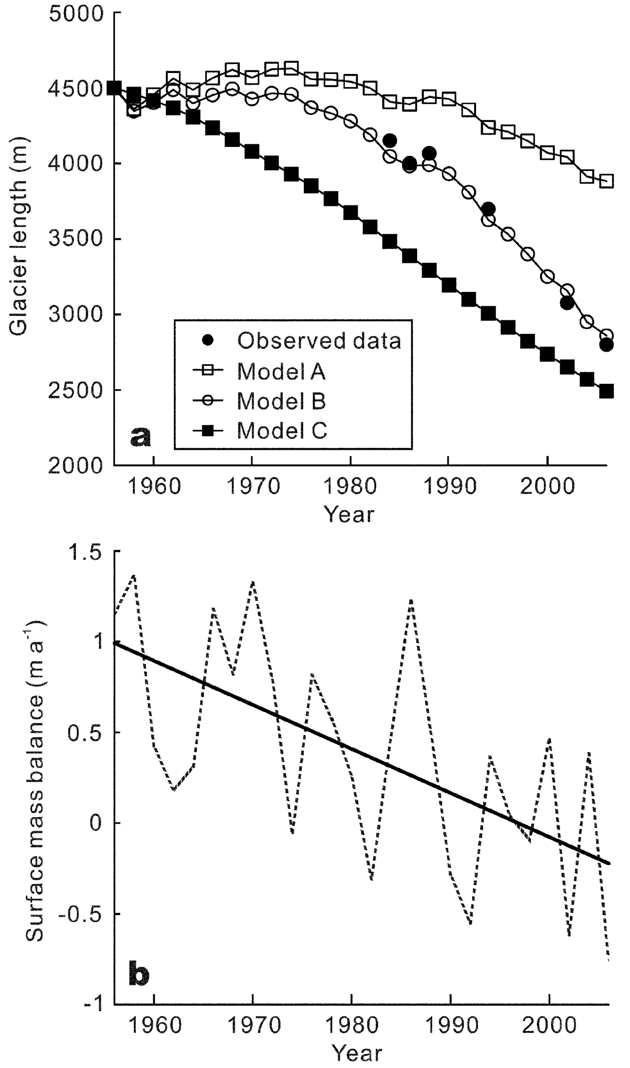

Fig. 5. Simulation results showing the variations of glacier length and surface mass balance. (a) shows changes of glacier length with the glacier simulation; model A is calculated with yearly variant surface mass balances, model B is conducted with both yearly variant mass balance and bathymetry data, and model C is simulated with a constant mass balance (0.54 m a^{-1}). Solid circles are observed glacier length. (b) shows the variations of calculated surface mass balance. Linear regression trend shows annual decreases in surface mass balance.

glacier. The results are illustrated in Figure 5a; model A is performed with yearly variant mass balance, model B is calculated with both basal topography and yearly variant mass balance, and model C is calculated with topography data and constant mass balance (0.54 m a^{-1}). In model A, the glacier displacement pattern is similar to model B but it retreats more slowly. In contrast, model C shows that the glacier terminus changes linearly. The retreat rate is faster than that of model B. Model B shows that the glacier front fluctuates within 100 m range until 1974. The linear regression trend of model B indicates that the mass balance in 1974 corresponded to 0.6 m a^{-1} (Fig. 5b).

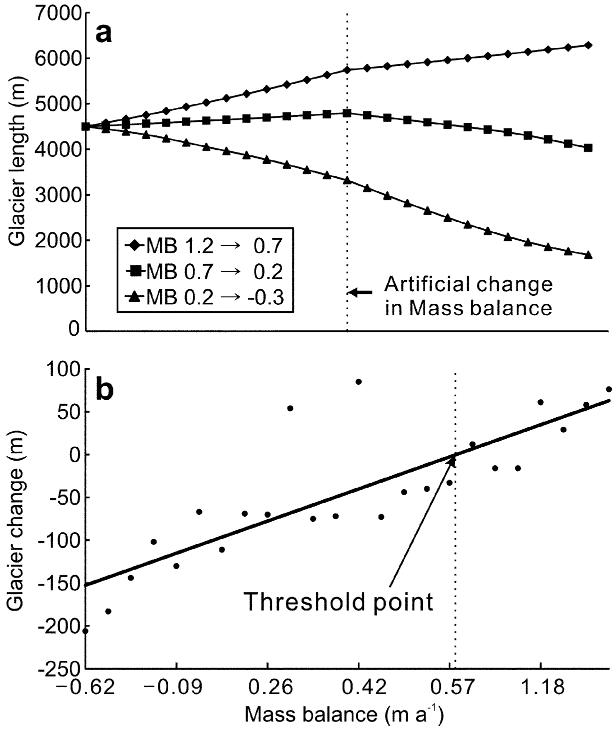

Fig. 6. Threshold point of glacier retreat. (a) shows relationship between glacier retreat and mass balance. Dotted vertical line indicates artificial changes in mass balance. Solid circles in (b) are the ratio of glacier changes versus mass balance from the model B (Fig. 5a). The value of 0.6 m a^{-1} is threshold point of the glacier retreat in Marian Cove.

Figure 6a shows the result of a simulation designed to understand the effects of the mass balance to the glacier retreat in Marian Cove. Mass balances are artificially changed with the same value of other parameters. The first model changes the mass balance from 1.2 to 0.7 m a^{-1}. Even if mass balance is reduced, the glacier advances for both cases. The second model varies mass balance from 0.7 to 0.2 m a^{-1}. The glacier advances until the mass balance changed. When the mass balance is changed to 0.2 m a^{-1}, the glacier starts to retreat. Finally, the glacier length is decreased with the mass balances from 0.2 to -0.3 m a^{-1}. As a result, there must be threshold point within the range from 0.7 to 0.2 m a^{-1} which determines whether the glacier advances or retreats in Marian Cove. The exact value of threshold point can be estimated from the surface mass balance versus glacier change plot as 0.6 m a^{-1} (Fig. 6b). This indicated that the continuous retreat of the glacier in Marian Cove except in 1986 is due to the decreased surface mass balance.

The glacier has been linearly retreated since 1984, with an advance from 1986 to 1988 (Chung et al., 2004). The simulation results also show same phenomena (Figs. 4 and 5a). We compare simulation results with observed data from period A, 1980-1982 and period B, 1986-1988 (Table 2). Two periods have very similar patterns in the points such as decreasing temperature, increasing ice velocity in a similar

Table 2. Comparison between two periods

	Period A: 1980~1982 (Retreat)	Period B: 1986~1988 (Advance)
Temperature (°C)	-4 ⇒ -1.8	-3.3 ⇒ -2.6
Ice velocity at terminus (m a^{-1})	86 ⇒ 103	88 ⇒ 94
Variation of altitude (m)	296 ⇒ 281	282 ⇒ 278
Surface mass balance (m a^{-1})	0.6 ⇒ -0.3	1.24 ⇒ 0.5
Glacier length (m)	4280 ⇒ 4190	3982 ⇒ 3992 (Modeled) 4000 ⇒ 4066 (Observed)

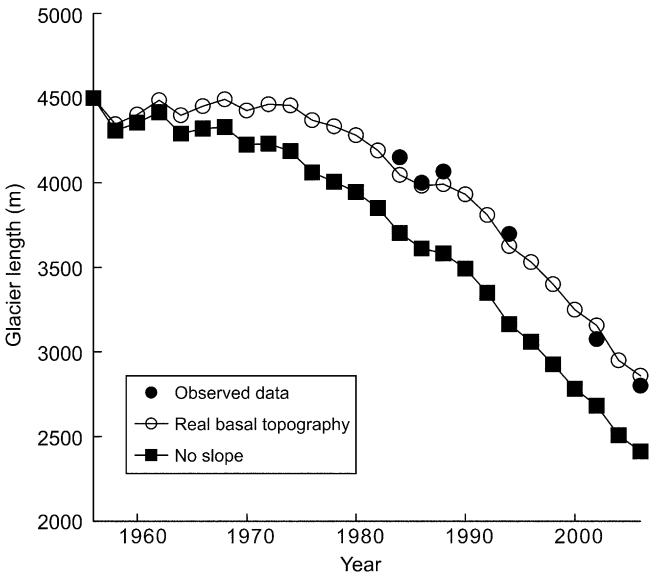

Fig. 7. The effect of topographical slope on the glacier movement. Solid squares are glacier front positions without the slope structure.

range, and decreasing altitude and mass balance. However, the glacier retreated during period A but advanced during period B. The main difference is that the lowest mass balance of period B is 0.5 m a^{-1} but that of period A is -0.3 m a^{-1}. The glacier advance during period B could be attributed to the mass balance of previous years (1984-1986), which is quite large compared with that of period A.

The bathymetry data shows a slope structure at the glacier front in 1956. This structure is around 60 m higher than the surroundings and 400 m wide. Figure 7 shows the effect of topographical slope on the glacier movement. The simulated calving rate is faster than that of observed data, and there is no advance phenomenon in 1988. This implies that the slope is not generated concurrently by repetition of glacier retreat and advance. Because the slope restricts advance of the glacier when the glacier front is located adjacent to the slope, the glacier was probably stabilized until 1974.

We predict future behavior of glacier front with the model developed in this study. The surface mass balances are calculated from the estimated air temperatures through current regional warming trend. For the basal elevation, we use the same data as previous calculations assuming that the highest point of the bed is 100 m above sea level. Figure 8 shows the forecast of glacier retreat. If global warming continues in the present trend, the glacier in Marian Cove is probably ice-free by 2060.

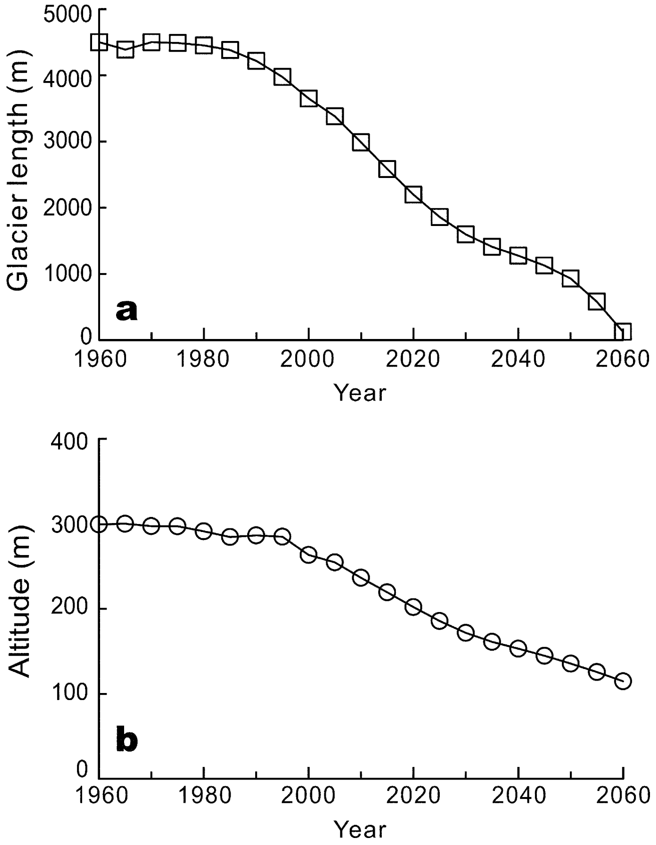

Fig. 8. Results of future behavior of the glacier. (a) and (b) are variations of the glacier length at the front position and altitude at the glacier submit, respectively. Because the glacier bed at the summit is 100 m both of glacier length and thickness are probably zero in 2060.

5. CONCLUSIONS

The results from our numerical model adequately explain displacements of the tidewater glacier in Marian Cove for the past 51 years. The results show that displacements of the glacier are dependent on the ice thickness at the terminus and on local surface mass balance. The mass balance of 0.6 m a^{-1} is the threshold point determining advance and retreat of tidewater glacier in Marian Cove, that is, the mass balance more than 0.6 m a^{-1} overcomes the yearly calving rate. Moreover, the mass balance of previous years also plays an important role in triggering glacier movement. The application of our model to predict future aspects shows that if the air temperature warming continues at 0.037 °C a^{-1}, the glacier is probably disappeared in Marian Cove by 2060.

We recognize that it is important to assign probabilities to this research, and this requires a more quantitative fundamental data set for modeling. In order to do this, monitoring the glacier mass balance and temporal variation of the glacier movement is necessary. The acquisition of bathymetry data in the cove and 3-dimmentional subglacial and surface topography of glacier is also essential for multi-dimensional glacier modeling.

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