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ICE FLOW AND MASS CHANGES OF LEWIS GLACIER, MOUNT KENYA, EAST AFRICA: OBSERVATIONS 1974-86, MODELLING, AND PREDICTIONS TO THE YEAR 2000 A.D.

By STEFAN HASTENRATH

(Department of Meteorology, University of Wisconsin–Madison, Madison, Wisconsin 53706, U.S.A.)

ABSTRACT. The study is based on an observation program since 1974, including the continuous monitoring of net balance during 1978–86. The 8 year vertical net-balance profile, characterized by negative values throughout and an increase of absolute amounts from the higher towards the lower elevations, defines the recent climatic forcing.

A model is developed with a spatial resolution by 100 m wide bands, relating glacier morphology, ice flow, and mass economy, using as input ice thickness, surface slope, width of height contours, area of 100 m wide bands, volume flux, and net balance as a function of elevation. In 1 year time steps, the model calculates the changes in ice thickness and surface topography commensurate with the difference between net balance and longitudinal divergence of volume flux, and then the corresponding changes in surface slope, contour width, area of 100 m wide bands, volume flux, and net balance corresponding to the new surface elevations. This information serves as input for the next time step.

The model was applied to the intervals 1974–78, 1978–82, and 1982–86, as training periods, to explore the diagnostics of ice flow and mass economy, and to ascertain the model performance in treating long-term evolution in glacier behavior. The experiments yielded a reasonable agreement between calculated and observed changes in ice thickness, velocity, and volume flux, over the three aforementioned 4 year periods of field monitoring. Two sets of prediction experiments beyond 1986 were then undertaken. The first used as input the observed 1978–86 vertical net-balance profile (a), and thus simulated the future evolution of the glacier given continuation of the recent climatic forcing. In the second set of experiments, the 1978–86 net-balance values were doubled to yield a more extreme net-balance profile (b), representing climatic conditions considerably more adverse to the maintenance of the glacier.

Predictions are presented for the epochs 1990, 1994, 1998, and 2000. Given continuation of the recent climatic conditions (profile a), the following changes are anticipated from 1986 to the year 2000: a shrinkage of the volume from 4 to 1 × 10^6 m^3; an area decrease from 25 to 17 × 10^4 m^2; a shortening of the glacier from 990 to less than 800 m; a slow-down of fastest ice flow from 2.5 to less than 1 m a^{-1}; a decrease of the maximum volume flux from 13 to less than 3 × 10^3 m^3 a^{-1}; and substantial up-glacier displacements of the velocity and volume-flux maxima. Under more extreme negative net-balance conditions (profile b), the decay would be so greatly accelerated that Lewis Glacier may completely disappear well before the end of the millennium. This prospect is inherent in a possible change from recent climatic conditions.

1. INTRODUCTION

Tropical glaciers are an especially climate-sensitive component of the environment and deserve particular attention in efforts at global climatic and environmental change (World Meteorological Organization-ICSU, 1975, p. 7, 11, 16; United Nations Environment Programme, 1979, p. 5-17; Permanent Service on the Fluctuations of Glaciers, IUGG-FAGS/ICSU, 1977, 1985; World Glacier Monitoring Service of IASH (ICSI)-UNEP-UNESCO, 1988). In the absence of comparable sustained observations anywhere else in the tropics, the long-term and ongoing field program on Lewis Glacier, Mount Kenya (Hastenrath, 1984, p. 143-84), is of considerable importance in the global context. Results of this project, including the reconstruction of glacier and climate variations since the latter part of the nineteenth century, have been regularly reported in this and other journals (Caukwell and Hastenrath, 1977, 1982; Hastenrath and Caukwell, 1979, 1987; Hastenrath and Kruss, 1979, 1982; Bhatt and others, 1980; Hastenrath, 1983, 1987a, b; Kruss, 1983, 1984; Kruss and Hastenrath, 1983). The objectives of the present study are to summarize observations during 1974–86, to introduce a model of ice flow and economy, and to predict the glacier behavior to

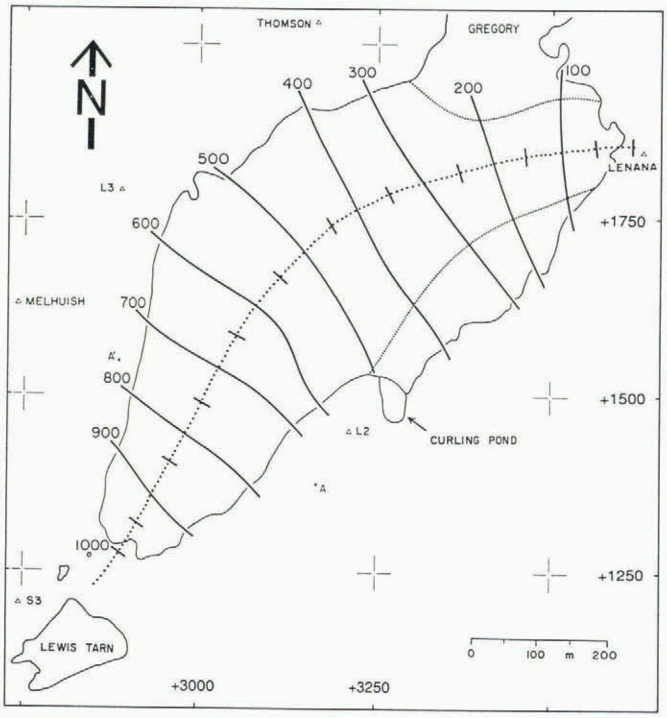

Fig. 1. Orientation map of Lewis Glacier. Arrow indicates north direction. Grid coordinates are local as in earlier maps (Forschungsunternehmen Nepal-Himalaya, 1967; Caukwell and Hastenrath, 1977, 1982; Hastenrath and Caukwell, 1979, 1987). The summit of Mount Kenya, to the north-west of Lewis Glacier (beyond map area), is at lat. 0°09′ S, long. 37°18′ E. Thin broken lines indicate ice-flow divides to the eastern part of Lewis Glacier and to Gregory Glacier in the north, respectively. Dotted line denotes central longitudinal line with tick marks entered at 50 m intervals. Solid lines define 100 m wide bands.

the end of the millennium, given continuation of the recent climatic conditions, as well as for a scenario of even more strongly negative net balance. Basic to this endeavor are the observations in the first 12 years of the project, in particular the continuous net-balance monitoring during 1978–86. These values serve as input to model calculations of flow velocity, volume flux, and ice-surface topography, volume, and extent.

2. OBSERVATIONS

For a comprehensive account of the long-term observation program refer to Hastenrath (1984, p. 143-284; 1987a, b). Only the measurements most pertinent to the present paper are summarized here, with reference to the orientation map in Figure 1.

Airborne mapping of the glacier-surface topography at a scale of 1 : 2500 was completed in February 1974, February 1978, March 1982, January 1985, and March 1986 (Caukwell and Hastenrath, 1977, 1982; Hastenrath and Caukwell, 1979, 1987). In combination with the determination of the bedrock topography and the ice-thickness pattern at the February 1978 datum, using seismological and gravimetric techniques, and numerical modelling (Bhatt and others, 1980), this repeated mapping of the glacier-surface topography permits the assessment not only of area and terminus variations but also of changes in ice thickness and volume. Thus, the map of ice thickness in March 1986 (Fig. 2) was constructed from the ice-thickness map with 1978 datum and airborne mapping of glacier-surface topography in 1978 and 1986.

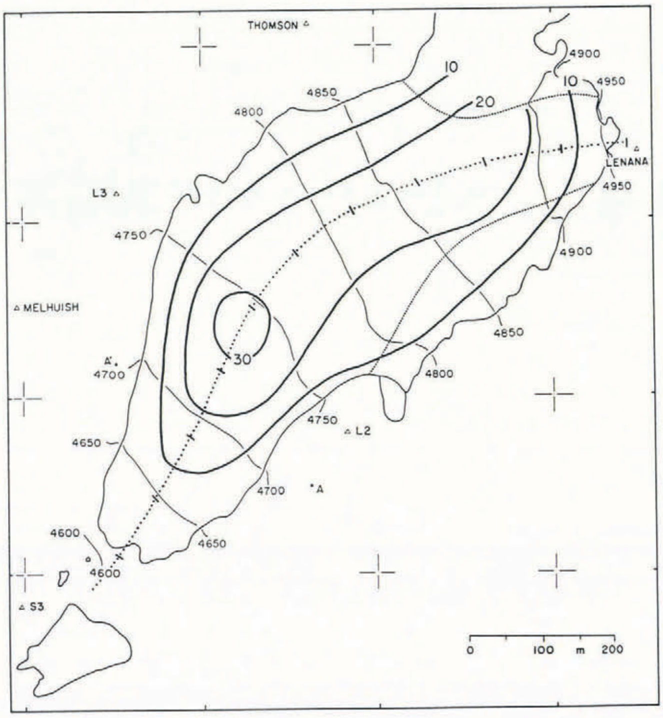

Fig. 2. Map of ice thickness in March 1986, in m. Other symbols as in Figure 1.

Net balance at a network of stakes has been monitored continuously since February 1978, and these observations are continuing (Hastenrath, 1983, 1984, p. 143-284; 1987a, b). In conjunction with repeated mapping of the glacier-surface topography, these measurements have elucidated the role of mass redistribution by the ice flow for the spatial pattern of surface powering (Hastenrath, 1983, 1987b). A vertical net-balance profile (a) constructed from the monitoring during 1978–86 is included in Figure 3.

The surface ice-flow velocity has been determined continuously since the beginning of 1978, through repeated surveying of the aforementioned stakes, of particular interest being the stations near the central line of flow (Fig. 1). In addition, ice-flow measurements have been made over shorter time intervals during 1973–74, 1958, and 1934; and

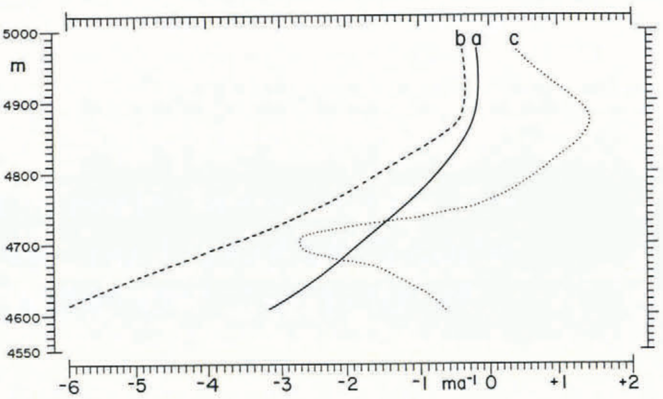

Fig. 3. Profiles of (geometric) net balance (m) as function of elevation: (a) measured 1978–86, solid; (b) values of "a" doubled, broken; (c) required to maintain 1986 volume flux (Fig. 5) and thickness (Fig. 2).

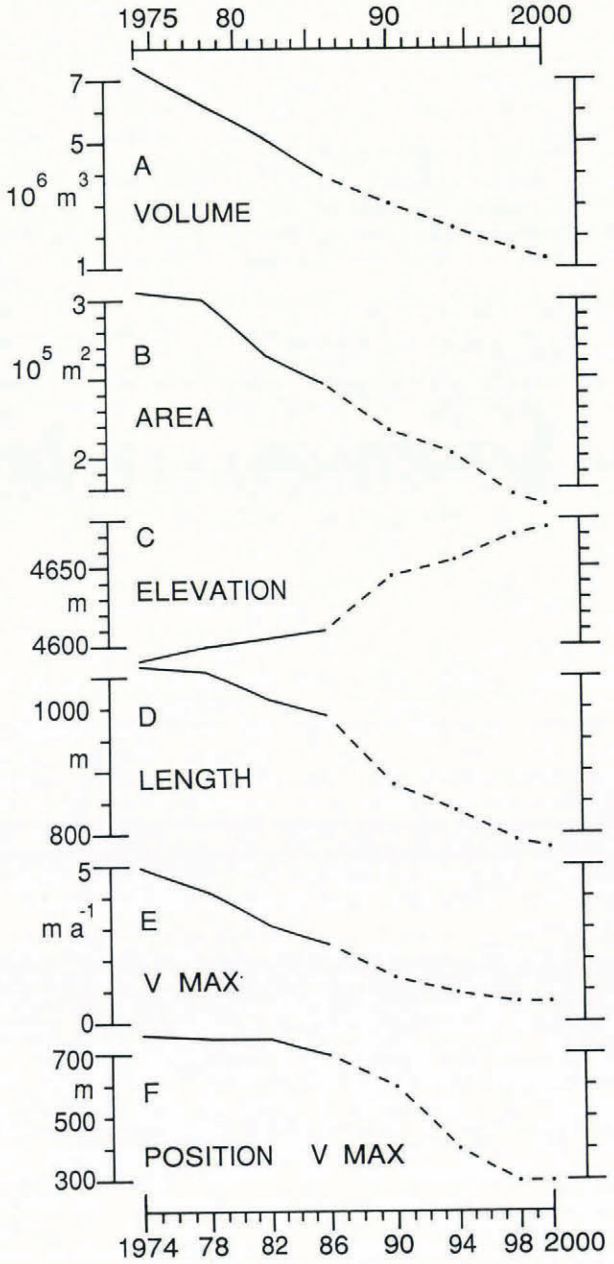

Fig. 4. Variations of Lewis Glacier 1974–2000. (a) Ice volume (10^6 m^3), (b) area (10^5 m^2), (c) terminus elevation (m), (d) terminus position (m), (e) maximum ice-flow velocity (m a^{-1}), (f) position of velocity maximum (m). Volume and area in (a) and (b) pertain to the entire glacier (western plus eastern parts; Fig. 1); and distances in (d) and (f) are counted along longitudinal axis from highest point of glacier (Fig. 1). Solid lines denote the observed period to 1986, and broken lines are predictions to the year 2000.

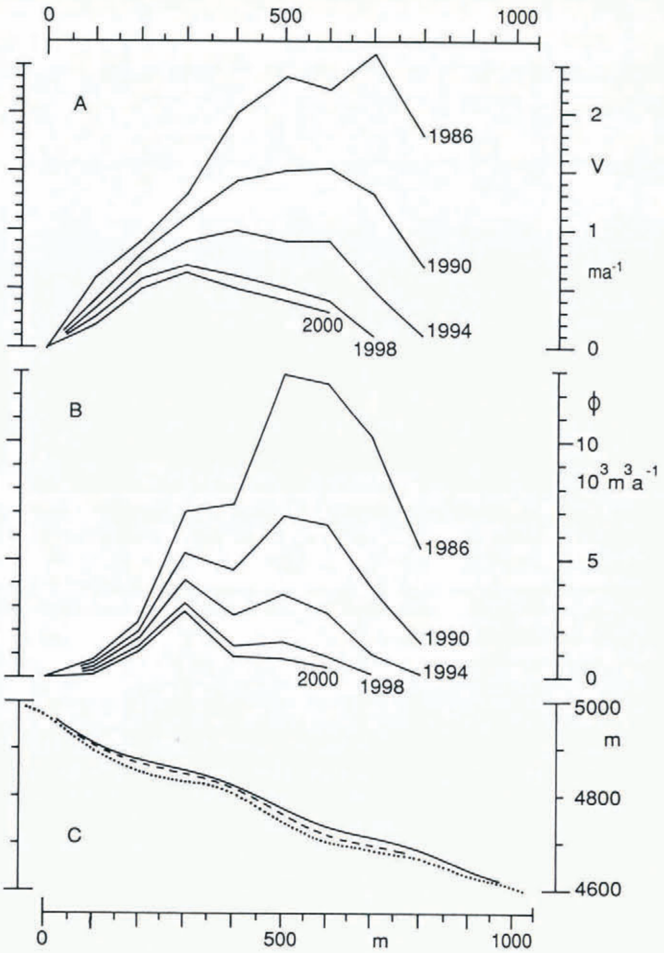

Fig. 5. Longitudinal profiles (Fig. 1) of (a) surface velocity (m a^{-1}); (b) volume flux (10^3 m^3 a^{-1}), for the years 1986, 1990, 1994, 1998, and 2000; (c) profiles of bedrock broken, ice surface 1986 solid, year 2000 dotted.

numerical modelling accomplished the reconstruction of the longitudinal velocity profile for various epochs back to the turn of the century (Hastenrath and Kruss, 1982; Hastenrath, 1984, p. 176-95). Ice-flow measurements up to 1986 are included in Figures 4 and 5.

3. CHANGES OF ICE FLOW, MASS BUDGET, AND VOLUME TO 1986

By way of background for the present study, Lewis Glacier experienced the following monotonic and drastic changes from the turn of the century to 1974 (Hastenrath, 1984, p. 170-81): (a) a decrease of the ice volume from about 380 to 74 × 10^5 m^3, (b) a decrease of the area from 627 to 306 × 10^3 m^2, (c) a rise of the terminus elevation by 125 m, and (d) a terminus retreat by 445 m, (e) a slow-down of the maximum ice flow from 15 to 5 m a^{-1}, and (f) a shift of the velocity maximum by 80 m up-glacier.

It is against this background that the much more comprehensively documented evolution since 1974 should be appreciated. Figure 4 (parts (a)–(d)) shows over the interval 1974–86 (a) a volume shrinkage from 74 to 39 × 10^5 m^3, (b) an area decrease from 306 to 247 ×10^3 m^2, (c) a rise of the terminus elevation by 18 m, and (d) a horizontal retreat of the terminus position by 73 m. Over the same 12 year period, Lewis Glacier experienced (e) a slow-down of the maximum flow velocity from 5 to less than 3 m a^{-1}, and (f) a further up-glacier displacement of the velocity by about 100 m.

The 1986 status of Lewis Glacier is illustrated in Figures 2, 4, and 5. This documentation of flow velocity, volume flux, ice thickness and extent, along with the 1978–86 monitoring of the vertical net-balance profile (Fig. 3), form the observational basis for modelling beyond 1986 (section 5) and predictions to the year 2000 (section 6).

4. BASIC THEORY

P. Kruss pioneered modelling the ice dynamics of Lewis Glacier (Bhatt and others, 1980; Hastenrath and Kruss, 1982, Kruss, 1984a, b). Directly pertinent here are only the relationships, described in Equations (5) and (6), between longitudinal volume flux ϕ, center-line surface velocity V_s, ice thickness Z, surface width W, surface-slope angle α, and various parameters, namely the constants n and k in a power flow law, stress-shape factor s, cross-section velocity ratio C_v, and valley power m; except for k all are dimensionless. These are introduced in the following equations.

In a power flow law, the vertically averaged deformational velocity

$$V_i = k\tau_b^n Z \qquad (1)$$

where τ_b is the center-line basal shear stress and Z is the ice thickness.

The stress-shape factor s is introduced by (Nye, 1965)

$$\tau_c = s\rho g \sin\alpha \qquad (2)$$

where $\tau_c \approx \tau_b$ is the center-line down-slope stress, ρ is the ice density (900 kg m^{-3}), and g is the gravitational acceleration (9.8 m s^{-2}).

The cross-sectional area

$$\Omega = \frac{m}{m+1} WZ. \qquad (3)$$

The cross-section velocity ratio

$$C_v = \bar{V}/V_s \qquad (4)$$

where $\bar{V}$ is the cross-section mean velocity.

As explained in Kruss (1984a, b), the constants in the power flow law are set to n = 2 and k = 0.16 bar^{-2} a^{-1} for Lewis Glacier. His numerical modelling yielded best correspondences for C_v = 0.7 and s = 0.9 in the upper glacier (longitudinal distances 0 to about 450 m), and s = 0.8 further down-glacier. $m \to \infty$ was used for longitudinal distances 0–450 m (Fig. 1), where the glacier boundaries are near to vertical as they are predominantly flow line or ice divide; and m = 2 further down-glacier. The center-line surface velocity, with a dimension m a^{-1} (Bhatt and others, 1980),

$$V_s = \left[\frac{n+2}{n+1}\right] k(s\rho g \sin\alpha)^n Z^{n+1} \qquad (5)$$

or essentially a function of ice thickness Z and surface slope α.

The volume flux, in m^3 a^{-1} (Hastenrath and Kruss, 1982), is

$$\phi = \left[\frac{m}{m+1}\right] C_v W Z V_s \qquad (6)$$

or essentially a function of center-line surface velocity V_s, ice thickness Z, and surface width W.

Equations (5) and (6) require information on the glacier morphology. The surface width W was evaluated from the maps of surface topography as lengths of height contours through the indicated points at 100 m spacing along the longitudinal axis (Fig. 1). For the same points, ice thickness Z was obtained from mapping the bedrock configuration and the surface topography (section 2). The surface-slope angle α was likewise read for these points from the maps of ice-surface topography.

5. MODELLING

The purpose of this section is to model ice flow and mass economy of Lewis Glacier given a vertical net-balance profile representing the climatic forcing. The model for

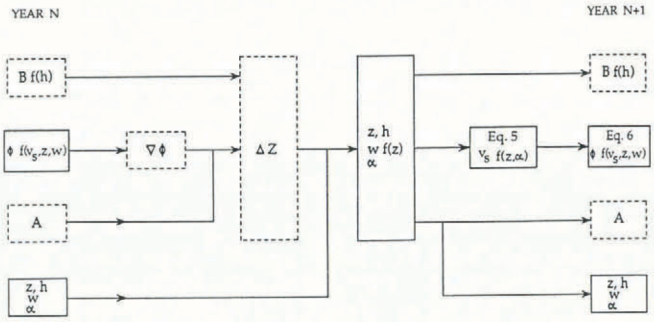

Fig. 6. Flow diagram illustrating the model for predicting ice thickness Z (m), center-line surface velocity V_S ($m\,a^{-1}$), and volume flux ϕ ($m^3\,a^{-1}$), bold symbols. Other symbols are as follows: B is geometric net balance ($m\,a^{-1}$); h is surface elevation (m); W is surface width (m); α is surface slope; A is area of bands (m^2); $\nabla\phi$ is net volume outflow from band ($m^3\,a^{-1}$); ΔZ is change in ice thickness over time step (m); f( ) is function of ( ); solid and broken-line boxes enclose values for equidistant center-line grid points and 100 m bands (Fig. 1), respectively.

calculating ice thickness Z, center-line surface velocity V_S, and volume flux ϕ, at the equidistant grid points (Fig. 1) is illustrated in Figure 6. A vertical net-balance profile representative of the recent climatic conditions is available from monitoring during 1978–86 (Fig. 3, curve "a"). From such a standard profile, net balance B is interpolated for the grid points spaced at 100 m intervals along the center line, and then for the 100 m wide bands (Fig. 1). As the surface elevation h for these discrete longitudinal distances and the 100 m wide bands vary with time, the corresponding net-balance values are recalculated.

In addition to the net balance B corresponding to the initial year (say 1974), surface elevations h and areas A of 100 m bands (Fig. 1), the initial (say 1974) status of volume flux ϕ, center-line velocity V_S, ice thickness Z, surface width W, and slope α at the equidistant center-line points, comprise the initial conditions. Regarding the surface width W, note that, in accordance with the ice-flow divide indicated in Figure 1, the eastern part of the glacier draining into Curling Pond is excluded here.

In a first 1 year time step, calculate for each 100 m wide band (Fig. 1), the volume change resulting from the prescribed net balance and lateral inflow and outflow of mass, and divide this volume by the area A of the band to obtain the corresponding change in surface elevation or ice thickness ΔZ. From the elevation changes in adjacent bands calculate the change in surface slope α at the 100 m spaced grid points. Separately, obtain the surface width W at 100 m intervals from a table constructed on the basis of the measured glacier morphology (Fig. 2) and relating W to Z. Insert the new Z and α into Equation (5) to obtain a new V_S. Insert the new V_S, Z, and W into Equation (6) to obtain a new volume flux ϕ. Also calculate new areas A for the 100 m wide bands, multiplying the previous A by the ratio of the arithmetic means of the new over the previous W at the upper and lower boundaries of the band.

For the next 1 year time step, interpolate new net-balance values corresponding to the new surface elevations of the 100 m bands. The new Z, W, α, and ϕ values ascribed to the center-line grid points, as well as the new A, complete the input for the next iteration.

In order to explore the performance of the model illustrated in Figure 6, it was applied to the intervals 1974–78, 1978–82, and 1982–86, as training periods. Thus, from the 1974 initial conditions, four 1 year time steps were used to calculate values for 1978 and analogous calculations were made for the other two 4 year periods. In Table I, computations are compared with the observed conditions in 1978, 1982, and 1986. Except for the interval 1974–78, when thickness and velocity changes were small and the flow velocity was less well observed, the root-mean-square differences between calculated and observed values are substantially smaller than the changes observed over the 4 year time span, typical root-mean-square differences being of the order of 2 m, $0.2\ m\,a^{-1}$, and $2 \times 10^3\ m^3\,a^{-1}$ for the changes in ice thickness, flow velocity, and volume flux, respectively.

TABLE I. EIGHT-POINT MEANS OF DECREASES IN ICE THICKNESS ΔZ, CENTER-LINE VELOCITY ΔV_S, AND VOLUME FLUX $\Delta\phi$, OVER THE INDICATED 4 YEAR INTERVALS ALONG WITH THE ROOT-MEAN-SQUARE DIFFERENCES d BETWEEN OBSERVED AND MODELLED VALUES

	ΔZ	d	ΔV_S	d	$\Delta\phi$	d
	m		$m\,a^{-1}$		$10^3\ m^3\,a^{-1}$	
1974–78	1.6	2.6	0.5	0.8	4	6
1978–82	4.2	2.4	1.0	0.3	9	2
1982–86	3.7	1.5	0.7	0.2	5	2

The modelled mass-budget characteristics of Lewis Glacier (western part, Fig. 1) for the 4 year intervals 1974–78, 1978–82, and 1982–86 are summarized in Table II, and compared with the observed volume changes. Note that all but the rightmost column of Table II result from modelling. The position of the volume-flux maximum for the western, main part of Lewis Glacier, at a longitudinal distance near 600 m (Fig. 1), separates the glacier into an upper domain of mass outflow and a lower area with inflow. For a closed flow entity, such as the western part of Lewis Glacier or the glacier as a whole, determinations of volume changes by "geodetic" (maps) and "glaciological" (stakes) methods agree within 10% in the 1978–82 and 1982–86 intervals, possessing both repeated topographic mapping and stake readings, as reported earlier (Hastenrath, 1983, 1987b). Thus, the observed 4 year volume changes for the entire western glacier listed in Table II are well established. Regarding the modelled totals for the three observed intervals, note that the observed 1978–86 net-balance profile (Fig. 3, curve a) was used throughout; net-balance values as a function of elevation were, if anything, somewhat less negative for 1982–86 than for 1978–82; and stake measurements of net balance are not available for 1974–78. With these qualifications, the modelled totals of volume decrease for the three time intervals are consistent with the magnitude of the observed changes.

Table II highlights the progressive change of the mass-budget characteristics of Lewis Glacier over the time span 1974–86. The drastic decrease of maximum volume flux implies that mass redistribution related to the flow dynamics became even less important for the mass economy of the upper and lower glacier. In the upper domain, the resultant volume loss exceeds the *in-situ* negative net balance, but this difference decreased from the first to the third quadrennium. In the lower domain, the volume loss is less than the net balance, but this difference also decreases with the volume flux. Table II shows over the three 4 year intervals an increase of negative values for the upper domain, but a decrease in the lower domain. The former feature may be related to the progressive topography decrease, bringing the glacier surface to lower elevations and making it more vulnerable to ablation. While this effect would also pertain to the lower glacier, it may be more than compensated by the elimination of the most vulnerable lower areas. The time intervals beyond 1986 in Table II will be discussed in section 6.

6. PREDICTION

The model sketched in Figure 6 relates glacier morphology, ice flow, and net balance or climatic forcing. Applications in section 5 to the period 1974–86 of field monitoring contributed to the diagnostics of ice flow and mass economy, but also served to appraise the model's ability to treat glacier evolution over extended time spans. In the present section, the model is used for predictions beyond 1986, the most recent observations used in this study. The aim is not climate forecasting, but rather the prediction of glacier response to climatic forcing as prescribed by a particular vertical net-balance profile.

Figure 3 contains three profiles of net balance. Profile "a" constructed from the 1978–86 measurements represents

TABLE II. MASS-BUDGET CHARACTERISTICS FOR INTERVALS 1974–78, 1978–82, 1982–86, 1986–90, 1990–94, 1994–98. NET BALANCE (BAL) AND VOLUME CHANGE (VOL) IN DOMAINS 0–600 m AND >600 m (FIG. 1), MASS FLUX AT 600 m ϕ_{600}, AND VOLUME CHANGE OF ENTIRE (WESTERN) GLACIER (TOT), AS MODELLED (MOD), AND OBSERVED (OBS). UNITS 10^3 m^3

	0–600 m		ϕ_{600}	*>600 m*		*TOT*	
	BAL	*VOL*		*BAL*	*VOL*	*MOD*	*OBS*
Part A							
1974–78	375	525	150	765	615	1140	1057
1978–82	335	460	125	680	555	1015	982
1982–86	365	440	75	550	475	915	1078
1986–90	355	395	40	445	405	800	
1990–94	345	365	20	350	330	695	
1994–98	335	345	10	295	285	630	
Part B							
1986–90	700	730	30	820	790	1520	
1990–94	665	670	5	445	450	1120	
1994–98	550	550	0	125	125	675	

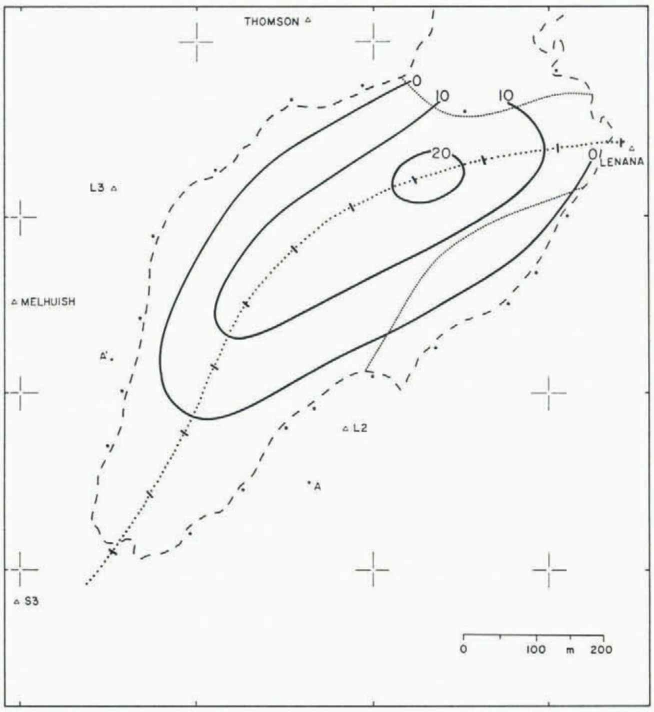

Fig. 7. Map of ice thickness (m) and extent predicted for the year 2000, using the observed 1978–86 net-balance profile (Fig. 3, curve "a"), solid lines; glacier boundaries 1986, broken. Other symbols as for Figure 1.

the recent climatic conditions. It shows negative net balance throughout, with an increase towards lower elevations where values in excess of -2 m a^{-1} are reached. Profile "a" is of foremost interest here and serves as input to a first set of experiments, with results presented in Figures 4, 5, and 7, and in parts A of Tables II–IV. This set of experiments models the evolution of Lewis Glacier under continuation of the recent climatic conditions. Alternatively, much attention has been given recently to the implications of a carbon-dioxide induced greenhouse effect and global warming (Gregory, 1988, p. 7-19, 306-15; Oerlemans, 1988). Such a development may substantially change the climatic forcing. With this consideration, the extremely unfavorable profile "b" in Figure 3 was constructed by doubling the negative values of the observed 1978–86 profile "a". Despite the extreme magnitudes, the profile maintains a plausible shape. This profile "b" serves as input to a second set of experiments, with results summarized in parts B of Tables II–IV. The third curve "c" in Figure 3 illustrates the vertical net-balance profile that would be required to maintain the 1986 volume flux and ice thickness. Unlike curves "a" and "b", the zig-zag shape of "c", especially below 4750 m, is implausible. This serves to underline that the recent shape and ice-flow pattern of Lewis Glacier are far from equilibrium conditions.

Figure 4 illustrates the changes of Lewis Glacier observed during 1974–86, along with the evolution beyond 1986 predicted given continuation of the recent climatic conditions (vertical net-balance profile "a" in Figure 3). On this basis, the following changes are anticipated from 1986 to the year 2000: (a) a shrinkage of the volume from 4 to 1 × 10^6 m^3; (b) an area decrease from 25 to 17 × 10^4 m^2; (c) a rise of the terminus by more than 80 m; (d) a shortening of the glacier from 990 to less than 800 m; and (e) a slow-down of the ice flow from 2.5 to less than 1 m a^{-1} maximum velocity, along with (f) a shift of the velocity maximum up-glacier by a longitudinal distance (Fig. 1) of 400 m.

Note that volume and area in parts (a) and (b) of Figure 4 refer to the entire glacier, that is its western plus eastern parts (Fig. 1). Area and volume of the western domain were obtained directly in the modelling described in section 5. Regarding the eastern domain, changes of ice thickness were assumed to be the same as for the respective longitudinal distances along the center line. From the values of ice thickness and the glacier morphology (Fig. 2), the length of contour lines (W) was derived. Changes in W of bounding contours in the eastern domain served to approximate changes in area, and changes in Z along with the area of these bands were used to estimate changes of volume. In conjunction with the information for 1986 (Fig. 2), this yields area and volume of the eastern domain for the epochs 1990, 1994, 1998, and 2000. The shares of the two domains are detailed in Table IV.

The evolution of the longitudinal profiles of ice-flow velocity and volume flux from 1986 to the year 2000 is further portrayed in Figure 5. Figure 5, part (a), details the progressive slow-down of ice flow and concomitant up-glacier shift of the velocity maximum summarized in Figure 4, parts (e) and (f). Figure 5, part (b), depicts the associated decay of the maximum volume flux from 13 to less than 3 × 10^3 m^3 a^{-1} along with the up-glacier displacement of the maximum by about 200 m of longitudinal distance (Fig. 1). Figure 5, part (c), finally illustrates the ice shrinkage in a longitudinal–vertical profile.

The graphical display in Figures 4 and 5 is complemented by the tabulations in part A of Tables II, III, and IV. In particular, columns Z and W of Table III, along with Figure 2, served to construct the map (Fig. 7) of ice thickness and extent predicted for the year 2000. Table II summarizes the mass-budget characteristics of Lewis Glacier for the 4 year intervals beyond 1986, to be compared with the period 1974–86 of direct observations. Part A of Table II serves to underline the further deterioration of mass-budget conditions beyond 1986. Thus, the volume discharge across the 600 m cross-section decreases drastically,

TABLE III. PREDICTIONS OF ICE THICKNESS Z (m), WIDTH W (m), CENTER-LINE SURFACE VELOCITY V_s (m a^{-1}), AND VOLUME FLUX ϕ (10^2 m^3 a^{-1}) AT INDICATED LONGITUDINAL DISTANCES (DIST) (m, FIG. 1) FOR 1990, 1994, 1998, AND 2000, USING "a" THE OBSERVED 1978–86 NET-BALANCE PROFILE, AND (b) VALUES OF "a" DOUBLED (FIG. 3, CURVES "a" AND "b")

Part A	*1990*				*1994*				*1998*				*2000*			
DIST	*Z*	*W*	*V*	*ϕ*	*Z*	*W*	*V*	*ϕ*	*Z*	*W*	*V*	*ϕ*	*Z*	*W*	*V*	*ϕ*
m																
100	11	142	0.4	5	10	142	0.3	3	9	142	0.3	2	9	142	0.2	2
200	23	155	0.8	19	21	155	0.7	16	20	155	0.6	13	19	155	0.5	11
300	26	273	1.1	53	25	272	0.9	41	23	270	0.7	32	23	270	0.7	28
400	17	262	1.4	45	15	252	1.0	26	13	243	0.6	13	12	235	0.5	9
500	24	406	1.5	69	20	389	0.9	35	16	371	0.5	15	14	346	0.4	8
600	28	337	1.5	65	23	277	0.9	27	18	232	0.4	9	15	213	0.3	4
700	22	281	1.3	39	16	251	0.5	10	9	219	0.1	1	6	209	0.0	0
800	17	275	0.7	14	9	221	0.1	1	–	–	–	–	–	–	–	–

Part B	*1990*				*1994*				*1998*				*2000*			
DIST	*Z*	*W*	*V*	*ϕ*	*Z*	*W*	*V*	*ϕ*	*Z*	*W*	*V*	*ϕ*	*Z*	*W*	*V*	*ϕ*
m																
100	10	142	0.4	4	9	142	0.2	2	7	142	0.1	1	6	142	0.1	1
200	22	155	0.7	17	19	155	0.6	12	17	155	0.4	8	16	155	0.4	6
300	25	272	1.0	46	22	270	0.7	29	19	261	0.5	17	17	256	0.4	12
400	15	253	1.0	26	10	220	0.3	5	5	158	0.0	0	2	125	0.0	0
500	20	389	1.0	37	12	321	0.3	5	3	207	0.0	0	–	–	–	–
600	23	275	0.9	27	12	191	0.2	2	–	–	–	–	–	–	–	–
700	15	249	0.5	9	1	187	0.0	0	–	–	–	–	–	–	–	–
800	8	216	0.1	1	–	–	–	–	–	–	–	–	–	–	–	–

TABLE IV. PREDICTIONS OF AREA (10^3 m^2) OF WESTERN (W) AND EASTERN (E) PARTS (FIG. 1) AND ENTIRE (TOT) GLACIER, FOR 1990, 1994, 1998, AND 2000, USING (a) THE OBSERVED 1974–86 NET-BALANCE PROFILE, AND (b) VALUES OF "a" DOUBLED (FIG. 3, CURVES "a" AND "b")

	1986	*1990*	*1994*	*1998*	*2000*
Part A					
Area					
W	217	191	177	152	146
E	29	27	25	24	23
TOT	246	218	202	176	169
Volume					
W	3284	2484	1789	1159	912
E	656	554	463	389	361
TOT	3940	3038	2252	1548	1273
Part B					
Area					
W	217	176	139	–	–
E	29	25	22	–	–
TOT	246	201	161	–	–
Volume					
W	3284	1764	644	–	–
E	656	520	375	–	–
TOT	3940	2285	1019	–	–

above all in consequence of the progressive thinning of the glacier (Table III, column 2). Accordingly, in the upper domain (longitudinal distance 0–600 m), the volume loss exceeds the negative net balance by an ever smaller amount, while in the lower domain (longitudinal distance >600 m) the excess of negative net balance over volume loss also decreases. The rate of volume loss per 4 years for the entire glacier also diminishes, due to the overall area decrease and the progressive elimination of the more vulnerable lower parts of the glacier. In fact, in appraising the gradual decrease of volume flux across the 600 m cross-section, it should be noted that the volume-flux maximum shifts progressively up-glacier (Fig. 5, part b), so that the glacier terminus draws ever closer to the 600 m grid distance (Fig. 4, part d).

A second set of experiments, using the vertical net-balance profile "b" in Figure 3, serves to explore the implications of climatic conditions even less favorable for the maintenance of the glacier than the recent 1978–86 period. Results are summarized only in tabular form, in part B of Tables II–IV, for convenient comparison with the predictions based on continuation of recent net-balance conditions (curve "a" in Fig. 3; part A of Tables II–IV; Figs 4 and 5). For such more severely negative net balance, comparison of thickness and flow values between parts B and A of Table III indicates a greatly accelerated decay of Lewis Glacier. Complementing Table III, Table IV (parts B and A) also shows for the 1990 and 1994 epochs much smaller areas and volumes for the more strongly negative net-balance condition. In part B of Table IV, no values are entered for 1998 and 2000, because after 1994 the thickness and volume values calculated from the "severe" net-balance profile (curve "b" in Figure 3) would result in an average ice thickness of well less than 5 m, the glacier mean tolerance of our determinations of ice thickness at the 1978 datum (Bhatt and others, 1980). In fact, Table III (part B) lists for 1998 and 2000 thickness values substantially above this threshold only at the 200 and 300 m grid points. Finally, Table II, summarizing the mass-budget characteristics for consecutive 4 year intervals, also shows in part B a particularly drastic deterioration, reflected in the rapid decrease of the volume flux across the 600 m cross-section, and the large total volume losses especially in the 1986–90 and 1990–94 intervals. The much smaller volume loss for 1994–98 appears commensurate with the greatly reduced total area (Table IV). Under severe net-balance conditions (curve "b" in Figure 3), however, that quadrennium may also feature the complete disappearance of Lewis Glacier.

7. SUMMARY AND CONCLUSIONS

The glaciers on the high mountains of East Africa have been receding ever since the earliest observations in the latter part of the last century (Hastenrath, 1984, p. 63-142). Inasmuch as tropical glaciers are a particularly climate-sensitive component of the environment, they deserve attention in relation to issues of global climatic change. However, in the entire tropics, a sustained monitoring program adequate for the quantitative study of cryosphere–climate relationships has only been maintained at Lewis Glacier on Mount Kenya. The systematic observation program since 1974 included the continuous monitoring of net balance during 1978–86, which establishes the recent climatic forcing.

Based on extensive earlier field and theoretical work, a model was developed relating glacier morphology, ice flow, and mass economy. This has a spatial resolution of 100 m wide bands, set by grid points along the central line of flow, and uses as input ice thickness, surface slope, width of height contours, area of 100 m wide bands, volume flux, and net balance as a function of elevation. The change of ice thickness and surface topography over 1 year time steps is calculated from the difference between net balance and the longitudinal divergence of volume flux. Implicit in the altered surface topography are changes of surface slope, contour width, area, and volume flux. Likewise, net balance pertaining to the various 100 m wide bands is computed in accordance with the new surface elevations. This information provides the input for the next time step.

In order to explore the diagnostics of ice flow and mass economy, and to appraise the model performance in treating long-term evolution, the model was applied to the intervals 1974–78, 1978–82, and 1982–86, as training periods. Over these time spans of field monitoring, the experiment yielded a reasonable agreement between calculated and observed changes in ice thickness, velocity, and volume flux.

On these grounds, two lines of experiment were conducted to predict evolution beyond 1986 and particularly to the epochs 1990, 1994, 1998, and 2000. These differed in the prescribed net-balance profile representing the climatic forcing. The first set was based on the observed 1978–86 vertical net-balance profile (curve "a" in Figure 3) and thus simulated the future evolution of the glacier under continuation of the recent climatic conditions. The second set of experiments used as input a much more extreme profile (curve "b" in Figure 3) with large negative net-balance values, to represent a change towards climatic conditions even less favorable than during 1978–86. Given continuation of the recent climatic conditions, the following changes are predicted from 1986 to the year 2000: a shrinkage of the volume from 4 to 1×10^6 m^3, an area decrease from 25 to 17×10^4 m^2, a shortening of the glacier from 990 to less than 800 m, a slow-down of the fastest ice flow from 2.5 to less than 1 m a^{-1}, a decrease of the maximum volume flux from 13 to less than 3×10^3 m^3 a^{-1}, and displacements of the velocity and volume-flux maxima up-glacier. However, under more extreme negative net-balance conditions, Lewis Glacier would decay much more rapidly and could in fact disappear completely well before the end of the millennium.

Some limitations to the ice-flow modelling (section 4) should be noted. A decrease of the ice thickness to only several meters may entail a slow-down of the ice flow more drastic than indicated by the model. However, a contrary effect may also be at play. Since 1986, the glacier has become seemingly wetter, and there are indications of a velocity increase despite the progressive thinning of the ice. As we have noted in our earlier work (Hastenrath, 1984, p. 180-87) accelerated flow during the January–February "dry" season, when melting is enhanced and the ice gets wetter, it is here hypothesized that increased liquid water content in the lower layers of the glacier may also on the decadal time-scale provide a lubrication conducive to faster flow. This effect may then counteract the velocity decrease due to thinning of the ice. Note that faster flow would entail more vigorous drainage of ice masses from the upper glacier, which in turn would serve to further aggravate the demise of Lewis Glacier.

The present prediction experiments were aimed at inferring the glacier response to climatic forcing, as prescribed by plausible vertical net-balance profiles. Although the model experiments included climatic conditions considerably more adverse to the health of the glacier than during the recent past, no attempt has been made here to forecast climate. The predictions offered are open to verification from future observations including not only glacier-surface topography and ice flow but also net balance as an integral expression of climate. The continued monitoring at this unique equatorial location is thus pertinent to the problem of global climatic change.

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