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# Quantifying the Mass Balance of Ice Caps on Severnaya Zemlya, Russian High Arctic. III: Sensitivity of Ice Caps in Severnaya Zemlya to Future Climate Change

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## Abstract

A coupled surface mass balance and ice-flow model was used to predict the response of three ice caps on Severnaya Zemlya, Russian Arctic, to the present climate and to future climate changes as postulated by the Intergovernmental Panel on Climate Change (IPCC). Ice cap boundary conditions are derived from recent airborne geophysical surveying (Dowdeswell et al., 2002), and model inputs are constructed from available climate data. Model results indicate that, currently, the state of balance of ice caps on Severnaya Zemlya is dependent on their size. For small ice caps, such as Pioneer Ice Cap (area 199 $km^2$), mass balance is extremely negative. Under current climate conditions, these relatively small ice caps are predicted to disappear within ~1000 years. For larger ice caps, however, such as the Academy of Sciences Ice Cap (area 5586 $km^2$), the accumulation zone is much larger, which results in these ice caps being approximately in balance today, but still susceptible to decay in future climate scenarios. When climate conditions are changed in the model, as predicted by the IPCC, the mass balance of all ice caps in Severnaya Zemlya is predicted to become negative within a 100 years or so. Although it is difficult to say with certainty the exact rate of decay, it is likely that ice loss from Severnaya Zemlya will contribute, over a period of a few hundred years, a rise in sea level of the order of a few centimeters.

## Introduction

Numerical modeling has shown that the climate sensitivity of ice caps and glaciers from different climatic settings varies by over an order of magnitude (e.g., Oerlemans and Fortuin, 1992; Fleming et al., 1997; Braithwaite and Zhang, 2000). It is believed that the sensitivity of ice masses is related to the annual precipitation, such that glaciers with a maritime influence are more sensitive than continental ones to climate change (Oerlemans and Fortuin, 1992). This notion is based on field measurements of mass balance and the results of modeling experiments for a selection of glaciers from across the globe. However, the dry subpolar glaciers and ice caps are poorly represented in studies of glacier responses to climate change, which are most often biased towards temperate valley glaciers (Oerlemans and Fortuin, 1992).

The aim of this paper is to assess the sensitivity of dry subpolar ice masses by quantifying the response of three ice caps in Severnaya Zemlya (Academy of Sciences, Vavilov, and Pioneer ice caps; Fig. 1) to climate change using a coupled mass balance ice-flow model detailed in Bassford et al. (2006a, 2006b), together with data sets of ice cap geometry derived from radio-echo sounding measurements (Dowdeswell et al., 2002). Mass balance modeling of the Vavilov Ice Cap reveals how refreezing of meltwater within the snowpack and directly onto the ice surface provides the bulk of ice accumulation (Bassford et al., 2006a). This modeling also reveals that there is a steep gradient in precipitation from southwest to northeast across the ice cap. When coupled to ice flow, the model reveals that the ice cap is actively migrating toward the moisture source across the land surface (Bassford et al., 2006b). However, the time-dependent reaction of this or any other ice cap on Severnaya Zemlya to future climate change has yet to be quantified.

In the first half of this paper, the static mass balance sensitivity of the three ice caps to climate change is examined. These results are compared with calculations from past studies for a sample of ice masses in different climate settings in order to test the idea that mass balance sensitivity is closely related to annual precipitation. The second half of this paper concerns the dynamic response of the Vavilov and Pioneer ice caps to a series of future climate change scenarios that have been used in an EISMINT modeling experiment on 12 different glaciers (Oerlemans et al., 1998). The sample of ice masses used in the EISMINT experiment was biased toward temperate valley glaciers. It is intended that results for the ice caps in Severnaya Zemlya will help to construct a more representative comprehension of the range in the response of ice masses to climate warming by accounting for dry subpolar ice caps. In a final simulation, the model is used to predict the response of the Vavilov and Pioneer ice caps to a seasonally differentiated climate change scenario specific to Severnaya Zemlya.

## Static Mass Balance Sensitivity of Ice Caps

Mass balance models of varying complexity have been used to predict the response of glaciers and ice caps around the world to changes in climate. The majority of studies follow a fixed geometry approach in which the sensitivity of mass balance to changes in temperature is defined for the present geometry of an ice mass. This is known as the *static* sensitivity to temperature $S_T$ of an ice cap or glacier, with units cm of water equivalent (w.e.) $a^{-1}$ $°C^{-1}$, and is calculated by

$$S_T = \frac{\partial B_m}{\partial T} \approx \frac{B_m(+1°C) - B_m(-1°C)}{2}, \quad (1)$$

where $B_m(x)$ is the mean net mass balance corresponding to a perturbation $x$ in temperature $T$ (Oerlemans et al., 1998). An estimate of the change in volume of an ice mass $\Delta V$ in response to a change in

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**FIGURE 1. Map of Severnaya Zemlya showing the locations of the Vavilov, Pioneer, and Academy of Sciences ice caps. The location of Severnaya Zemlya within the Eurasian Arctic is inset.**

temperature can be made by multiplying the static sensitivity with the initial area of the ice mass $A(t_0)$ and the integral of the temperature perturbation over the time period considered $(t - t_0)$:

$$\Delta V = S_T A(t_0) \int_{t_0}^{t} T' dt. \quad (2)$$

Equations 1 and 2 can also be applied to calculate the static sensitivity to perturbations in precipitation $S_P$, with units cm w.e. $a^{-1}$ $\%^{-1}$, and the resulting changes in ice volume.

The advantage of the fixed geometry approach is that the static sensitivity can be readily calculated for many glaciers and ice caps using a mass balance model with climate and hypsometry data (e.g., Oerlemans and Fortuin, 1992; Gregory and Oerlemans, 1998). However, this approach is usually only valid for short time periods because of the effect of changing geometry on mass balance. Nonetheless, it is still interesting to examine the static sensitivity of ice caps and glaciers since it represents the immediate response of ice masses to climate change.

**TABLE 1**

**Mean equilibrium line altitude (ELA) of the Vavilov, Academy of Sciences, and Pioneer ice caps for the period 1962–1966, based on field measurements reported by Govorukha (1988). A range is given for the Vavilov and Academy of Sciences ice caps, reflecting the spatial variation in ELA caused by gradients in precipitation (see Bassford et al., 2006b, for details of the Vavilov Ice Cap).**

| Ice cap | Mean ELA (m a.s.l.) |
|---|---|
| Vavilov | 430–500 |
| Academy of Sciences | 370–450 |
| Pioneer | 350 |

*THE REFERENCE STATES*

The first step in calculating the static sensitivity of an ice cap is to use a model to define a reference mass balance, ideally representative of the present state of the ice cap. This has been done for the Vavilov Ice Cap by calibrating a distributed model using mass balance measurements and a "reference climate" (Bassford et al., 2006a). The reference climate is defined by Bassford et al. (2006a) as being "constructed from meteorological data and used to describe the climatic regime of the Vavilov Ice Cap . . . for the periods 1974–1981 and 1985–1988". Unfortunately, there are relatively few mass balance data available for the Academy of Sciences and Pioneer ice caps. Probably the most useful information available about the mass balance of these ice caps comprises measurements of the equilibrium line altitude (ELA) during the period 1962–1966 (Table 1). The range of 430–500 m a.s.l. for the mean ELA of the Vavilov Ice Cap is compatible with a mean value of 498 m a.s.l. for the period 1974–1988, based on independent measurements (Barkov et al., 1992). This suggests that data for all of the ice caps collected during the relatively short period of 1962–1966 are probably representative of the mean conditions between the years 1974 and 1988. Additional information about the long-term mean annual mass balance at the summit of the



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Academy of Sciences Ice Cap has recently been obtained from a deep ice core extracted in 1998 at the ice cap crest. Analyses of the upper 54 m of the core have detected the 1963 maximum of artificial radioactivity from atmospheric nuclear tests, and $^{137}$Cesium marks the depth of the layer corresponding to the Chernobyl disaster in 1986. The resulting mean annual net mass balance at this site, integrated over these periods, is 45 cm $a^{-1}$ from 1963 and 55 cm $a^{-1}$ from the 1986 horizon (Fritzsche et al., 2002).

Similarly, there is a lack of published climate data for the Academy of Sciences and Pioneer ice caps. Meteorological data have recently been recorded for short time periods of less than two years at temporary stations in the accumulation areas of these ice caps, but the data are fragmentary and may not be representative of typical conditions (Koerner, personal communication).

The dearth of climate and mass balance data makes it difficult to calibrate distributed mass balance models of the present state of the Academy of Sciences and Pioneer ice caps. However, modeling can still be used to assess the sensitivity of these ice caps to climate change. Therefore, models were constructed for the Academy of Sciences and Pioneer ice caps, based on the model applied to the Vavilov Ice Cap in Bassford et al. (2006b). The reference climate defined for the Vavilov Ice Cap was extrapolated to represent conditions on the other ice caps. This is a viable approach since the distance between the Vavilov Station and the central parts of the Academy of Sciences and Pioneer ice caps is only about 125 km and 70 km, respectively. All other parameters were set to the same values as those used in the coupled model of the Vavilov Ice Cap (Bassford et al., 2006a, 2006b).

The main challenge in constructing the new models was determining the distribution of precipitation over the Academy of Sciences and Pioneer ice caps. The position of the transient snowline identified in Landsat images acquired in late summer suggests that a gradient in precipitation exists over these two ice caps, similar to that observed for the Vavilov Ice Cap, i.e. snowfall is greatest in the southwest and decreases moving northeast. However, it is very difficult to determine an accurate precipitation field over the ice caps without at least a few winter accumulation measurements to validate results. Therefore, an assumption was made that precipitation is a function of altitude. To calculate the gradient in precipitation with altitude for the Academy of Sciences Ice Cap, the model was tuned by adjusting the amount of precipitation to calculate the observed mass balance at the following two points on the ice cap: (1) the equilibrium line, assumed to have an altitude of 410 m a.s.l., falling in the center of the range of values listed in Table 1, and (2) the summit of the ice cap at an altitude of 749 m a.s.l., where the long-term mean annual net mass balance is reported to be 45 cm $a^{-1}$ (Fritzsche et al., 2002). Results from this procedure, given in Table 2, appear plausible and are within the range of annual precipitation determined for the Vavilov Ice Cap (Bassford et al., 2006b).

The two values of precipitation were then used to derive the following equation, expressing precipitation $p$ as a linear function of altitude $h$:

$$p = 0.021h + 46.4, \quad (3)$$

where $p$ has units cm w.e. $a^{-1}$ and $h$ has units m a.s.l. A similar procedure was repeated for the Pioneer Ice Cap using an ELA of 350 m a.s.l. (Table 1) and a precipitation gradient equal to that determined for the Academy of Sciences Ice Cap. The resulting equation is

$$p = 0.021h + 51.7. \quad (4)$$

The models of the Academy of Sciences and Pioneer ice caps were then used to calculate a reference mass balance for each ice cap. The reference states of these ice caps, together with that calculated for the Vavilov Ice Cap in Bassford et al. (2006b), are shown in Figure 2 and their characteristics are summarized in Table 3.

**TABLE 2**

**Results from tuning the mass balance model to determine the precipitation at two points on the Academy of Sciences Ice Cap.**

| | Location on the ice cap | |
|---|---|---|
| | ELA (410 m a.s.l.) | Summit (749 m a.s.l.) |
| Observed mass balance | 0 cm w.e. $a^{-1}$ | 45 cm w.e. $a^{-1}$ |
| Calculated mass balance | 0 cm w.e. $a^{-1}$ | 45 cm w.e. $a^{-1}$ |
| Derived precipitation | 55 cm w.e. $a^{-1}$ | 62 cm w.e. $a^{-1}$ |

With the exception of Vavilov Ice Cap, the model results in Table 3 cannot be interpreted as an accurate calculation of the present state of the ice caps. However, the results suggest that the Pioneer Ice Cap has a significantly negative mass balance under present conditions, reflected by a low accumulation area ratio, while the surface mass balance of the Academy of Sciences Ice Cap is approximately zero. The volume of ice lost by iceberg calving at the marine margins of the Academy of Sciences Ice Cap is estimated to be about 0.65 $km^3$ $a^{-1}$ (Dowdeswell et al., 2002), equivalent to a mean mass loss of 12 cm $a^{-1}$ over the whole of the ice cap. Therefore, the overall mean net mass balance of the Academy of Sciences Ice Cap, including the mass lost through calving, is calculated to be –13 cm $a^{-1}$ for the reference state. However, mass loss through iceberg calving is neglected in the rest of this paper since the focus is on the sensitivity of *surface* mass balance to climate change.

## *CLIMATE SENSITIVITY*

After defining the reference states for the Vavilov, Academy of Sciences, and Pioneer ice caps, the static sensitivity of these ice caps was determined by recalculating the mass balance with uniform changes of ±1°C in air temperature throughout the year. Similarly, the effects of changes in precipitation on mass balance were assessed by running the models with changes of ±10% in precipitation. Results from these simulations and the corresponding sensitivities of each ice cap are presented in Tables 4 and 5, while modeled mass balance profiles are shown in Figure 3.

The static sensitivity of mean net mass balance to temperature change is similar for each ice cap (Table 5), with a mean value of –36 cm w.e. $a^{-1}$ $°C^{-1}$. In general, the greatest changes in mass balance occur at the margins of the three ice caps, with a progressively lower sensitivity with increasing altitude, in agreement with other mass balance modeling studies (e.g., Oerlemans and Hoogendoorn, 1989; Fleming et al., 1997). Two factors are responsible for this: (1) the albedo feedback is stronger in the ablation zone, and (2) the amount of meltwater refreezing in the snowpack and on the ice surface to form superimposed ice tends to buffer changes in the intensity of surface melting in the accumulation zone. Modeling results suggest that the three ice caps have a much lower sensitivity to precipitation than to temperature change, reflected by small changes of about 1 cm w.e. $a^{-1}$ $\%^{-1}$ in mean net mass balance.

Perturbations in temperature result in considerable changes in the ELA, ranging from 175 to 241 m $°C^{-1}$. Since the altitudinal range of the three ice caps is quite small, changes in the ELA of this order will have a large effect on the size of the ablation and accumulation zones. In fact, an increase in temperature of 1°C causes the ELA to rise above the summit of Pioneer Ice Cap (Fig. 3), resulting eventually in the complete wastage of the ice cap. The ELA of the Vavilov Ice Cap is significantly less sensitive to changes in temperature relative to the



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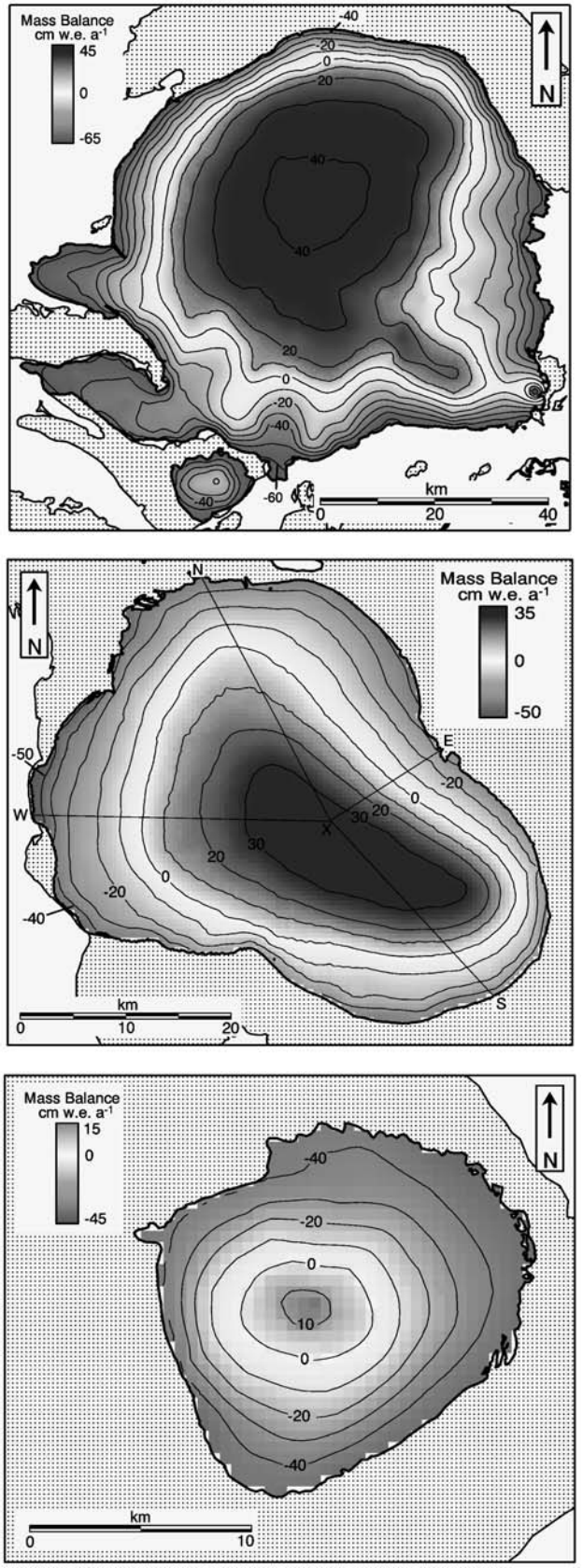



**FIGURE 2. Modeled mass balance of three ice caps in Severnaya Zemlya (using the reference climate). (a) Academy of Sciences Ice Cap. Isolines are at intervals of 10 cm w.e. $a^{-1}$. (b) Vavilov Ice Cap. Mass balance profiles N-X, E-X, S-X, and W-X are shown in Figure 3. (c) Pioneer Ice Cap. Isolines are at intervals of 10 cm w.e. $a^{-1}$.**

**TABLE 3**

**Characteristics of the reference mass balance calculated by modelling the Vavilov, Academy of Sciences, and Pioneer ice caps.**

| | Ice cap | | |
|---|---|---|---|
| | Vavilov | Academy of Sciences | Pioneer |
| Area of accumulation zone ($km^2$) | 810 | 2885 | 21 |
| Area of ablation zone ($km^2$) | 961 | 2701 | 178 |
| Accumulation area ratio | 0.45 | 0.52 | 0.12 |
| Equilibrium line altitude (m a.s.l.) | 350–621 | 410 | 350 |
| Mean net surface mass balance (cm w.e. $a^{-1}$) | −2 | −1 | −25 |

other ice caps. This is because of the steeper gradients of mass balance with altitude close to the ELA of the Vavilov Ice Cap, associated with the precipitation field over the ice cap (Fig. 3). The fact that the Vavilov Ice Cap has a similar mass balance sensitivity to the other ice caps, despite the much lower sensitivity of the ELA, is due to a combination of the different mass balance gradients and hypsometries of the three ice caps.

Since there have been few mass balance modeling studies of High Arctic glaciers and ice caps, it is worthwhile comparing the static sensitivities of the Vavilov, Academy of Sciences, and Pioneer ice caps with results from previous energy balance calculations for glaciers in different climate regimes (Oerlemans and Fortuin, 1992; Fleming et al., 1997). Figure 4 shows a compilation of results for changes in mean net mass balance resulting from a 1°C increase in temperature, plotted against the mean annual precipitation for a variety of ice caps and glaciers. Changes on the order of –40 cm w.e. $a^{-1}$ in the net mass balance of ice caps on Severnaya Zemlya compare with values around –12 cm w.e. $a^{-1}$ for ice masses in the Canadian High Arctic and values ranging between –60 and –80 cm w.e. $a^{-1}$ for alpine glaciers. The most sensitive ice masses from those shown in Figure 4 are the glaciers in western Norway with predicted changes in mass balance of up to –115 cm w.e. $a^{-1}$.

The calculated mass balance sensitivity of ice caps on Severnaya Zemlya supports the idea that ice masses located in a wetter climate (i.e., greater accumulation) are more sensitive to climate change. Several factors explain this relationship (Oerlemans and Fortuin, 1992). Glaciers with a large mass turnover usually extend to lower altitudes with a warmer climate. Under these conditions, changes in temperature have a large effect on accumulation by changing the proportion of precipitation falling as snow. This effect is much less important for the drier subpolar glaciers and ice caps, where virtually all precipitation falls as snow. Furthermore, the relation between surface melting and air temperature is not linear since melting only occurs when temperatures approach 0°C. Therefore, a rise in

**TABLE 4**

**Mean net mass balance ($B_m$) and mean equilibrium line altitude (ELA) of the Vavilov, Academy of Sciences, and Pioneer ice caps for four climate change experiments. $B_m$ and ELA have units of cm w.e. $a^{-1}$ and m a.s.l., respectively. The ELA exceeds the summit of the Pioneer Ice Cap for a 1°C warming.**

| | Vavilov | | Academy of Sciences | | Pioneer | |
|---|---|---|---|---|---|---|
| Model run | $B_m$ | ELA | $B_m$ | ELA | $B_m$ | ELA |
| Reference state | −2 | 498 | −1 | 410 | −25 | 350 |
| 1°C warming | −40 | 664 | −40 | 636 | −66 | >410 |
| 1°C cooling | 28 | 315 | 29 | 155 | 14 | 109 |
| +10% precipitation | 11 | 437 | 7 | 339 | −14 | 288 |
| −10% precipitation | −10 | 543 | −9 | 450 | −35 | 398 |



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temperature in a maritime regime is likely to significantly increase the length of the melting season, while a similar change in climate will have little effect in a subpolar region where temperatures will remain well below zero for much of the year.

### *SEASONAL SENSITIVITY CHARACTERISTIC*

Atmospheric general circulation models predict that future changes in temperature associated with an enhanced greenhouse effect will be greatest in winter months and somewhat smaller during the summer at high northern latitudes (IPCC, 2001). It is, therefore, interesting to examine how climatic changes in different seasons influence the mass balance of ice caps on Severnaya Zemlya. Seasonal changes were investigated using a method known as the seasonal sensitivity characteristic (SSC) which describes the dependence of the mean net mass balance of an ice mass on monthly perturbations in temperature and precipitation (Oerlemans and Reichert, 2000). The general idea is that changes in mass balance in a particular year, $\Delta B_{\mathrm{m}}$, relative to a reference mass balance, $B_{\mathrm{m,ref}}$, can be related to monthly mean temperature, $T_k$, and precipitation, $P_k$, by

$$\Delta B_{\mathrm{m}} = B_{\mathrm{m}} - B_{\mathrm{m,ref}} = \sum_{k=1}^{12}\left[C_{T,k}(T_k - T_{\mathrm{ref},k}) + C_{P,k}\left(\frac{P_k}{P_{\mathrm{ref},k}} - 1\right)\right] + H, \quad (5)$$

where

$$C_{T,k} = \frac{\partial B}{\partial T_k} \quad (6)$$

$$C_{P,k} = \frac{\partial B}{\partial (P_k / P_{\mathrm{ref},k})}. \quad (7)$$

The subscript $k$ refers to the month and takes the values $k = 1, 2 \ldots 12$. $T_{\mathrm{ref},k}$ and $P_{\mathrm{ref},k}$ are the monthly mean values of temperature and precipitation associated with the reference mass balance. $C_{T,k}$ and $C_{P,k}$ have units cm w.e. °C$^{-1}$ and cm w.e., respectively (Oerlemans and Reichert, 2000). The term $H$ represents all nonlinear terms, including feedbacks in the system and mutual interference of monthly perturbations. For example, the effect of a temperature perturbation in July may be affected to some extent by a change in precipitation during the previous month. Oerlemans and Reichert (2000) found that such effects are not very significant if the perturbations in monthly mean temperature and precipitation do not exceed about 2°C and 40%, respectively. Therefore, $H$ is neglected in this study. The SSC comprises a $2 \times 12$ matrix of values for $C_{T,k}$ and $C_{P,k}$ which were determined by running the mass balance model for monthly perturbations in temperature (+0.5°C and –0.5°C) and precipitation (−10% and +10%). For a more detailed description of the calculation of the SSC see Oerlemans and Reichert (2000).

The SSC for the Vavilov, Academy of Sciences, and Pioneer ice caps are shown in Figure 5, together with results from Oerlemans and Reichert (2000) for three other glaciers in different climatic regimes. A striking feature of the SSC of the three ice caps in Severnaya Zemlya is that the temperature sensitivity is determined almost entirely by the summer months (June, July, and August). Temperature perturbations in other months have a negligible effect on mass balance. This is also the case for White Glacier in the Canadian High Arctic which is located at a similar latitude (~79°N) to the ice caps in Severnaya Zemlya, although the climate is even drier there, with a mean annual precipitation of about 25 cm w.e. The melt season is much longer for Hintereisferner, and changes in temperature between March and October have a significant effect on mass balance. In the most extreme case of Franz Josef Glacier in New Zealand, which has a strong maritime influence and a mean annual precipitation of ~6 m w.e., mass balance is very sensitive to changes in temperature throughout the year, including the winter months.

**TABLE 5**

**Static sensitivity to temperature and precipitation of the mean net mass balance ($S_T$ and $S_P$) and equilibrium line altitude (dELA/dT and dELA/dP) of the Vavilov, Academy of Sciences, and Pioneer ice caps. Given are the mean values calculated using results from the positive and negative perturbation experiments (Table 4).**

| | Vavilov | Academy of Sciences | Pioneer | Mean |
|---|---|---|---|---|
| $S_T$ (cm w.e. a$^{-1}$ °C$^{-1}$) | −34 | −35 | −40 | −36 |
| dELA/dT (m °C$^{-1}$) | 175 | 240 | 241 | 219 |
| $S_P$ (cm w.e. a$^{-1}$ %$^{-1}$) | 1 | 1 | 1 | 1 |
| dELA/dP (m %$^{-1}$) | −5 | −6 | −6 | −6 |

Seasonal variations in $C_{P,k}$ for the ice caps in Severnaya Zemlya reflect to a large extent the distribution of precipitation through the year, although the very low values of $C_{P,k}$ in July and August occur because a significant fraction of precipitation falls as rain in these months and is lost from the ice cap as runoff. This implies that summer precipitation is less important for mass balance than precipitation falling as snow during the rest of the year. The greater sensitivity to fractional changes in precipitation of Hintereisferner and Franz Josef Glacier reflects the much wetter climate in these locations, particularly in the latter case. In contrast to ice caps in Severnaya Zemlya, summer precipitation makes a significant contribution to the annual balance of these glaciers because of summer snowfall high up in the accumulation zone.

An interesting result from this comparison is the high value of $C_{T,7}$ (i.e., July) for ice caps in Severnaya Zemlya, which is much greater than that of White Glacier and Hintereisferner and of a similar magnitude to Franz Josef Glacier in mid-summer. Probably the most important factor explaining this is the hypsometry of the ice caps in Severnaya Zemlya, which is characterized by a small altitudinal range (<750 m) with a lower limit close to sea level. Therefore, in summer, a rise in temperature at sea level results in a significant increase in melting even at the summit of the ice caps, together with a considerable reduction in the amount of precipitation falling as snow. The other glaciers have a much greater altitudinal range (e.g., White Glacier: 200–1600 m a.s.l.; Hintereisferner: 2600–3600 m a.s.l.) and so changes in temperature at lower elevations have a relatively small effect on melting and the form of precipitation in the upper accumulation area. Another possible factor explaining the relatively high values of $C_{T,7}$ calculated for ice caps in Severnaya Zemlya is the treatment of albedo in the model, which differs from the scheme used by Oerlemans and Reichert (2000) where albedo is a function related to the distance from the equilibrium line altitude. The treatment of albedo has a large effect on the intensity of the albedo feedback, which is an important influence on the modeled sensitivity of a glacier (Oerlemans, personal communication).

To quantify the seasonality in the effect of temperature perturbations on the annual mass balance, Oerlemans and Reichert (2000) define a seasonality index *SI*:

$$SI = \frac{C_{T,6} + C_{T,7} + C_{T,8}}{\sum_{k=1}^{12} C_{T,k}}. \quad (8)$$

Values of the *SI* for the Vavilov, Academy of Sciences, and Pioneer ice caps are 0.97, 0.97, and 0.98, respectively, and are plotted, together with calculations conducted by Oerlemans and Reichert (2000) for 14 other glaciers, against annual precipitation in Figure 6. The results for ice caps in Severnaya Zemlya fit with the general conclusion reached by Oerlemans and Reichert (2000) that the sensitivity of a glacier or ice cap to changes in temperature is



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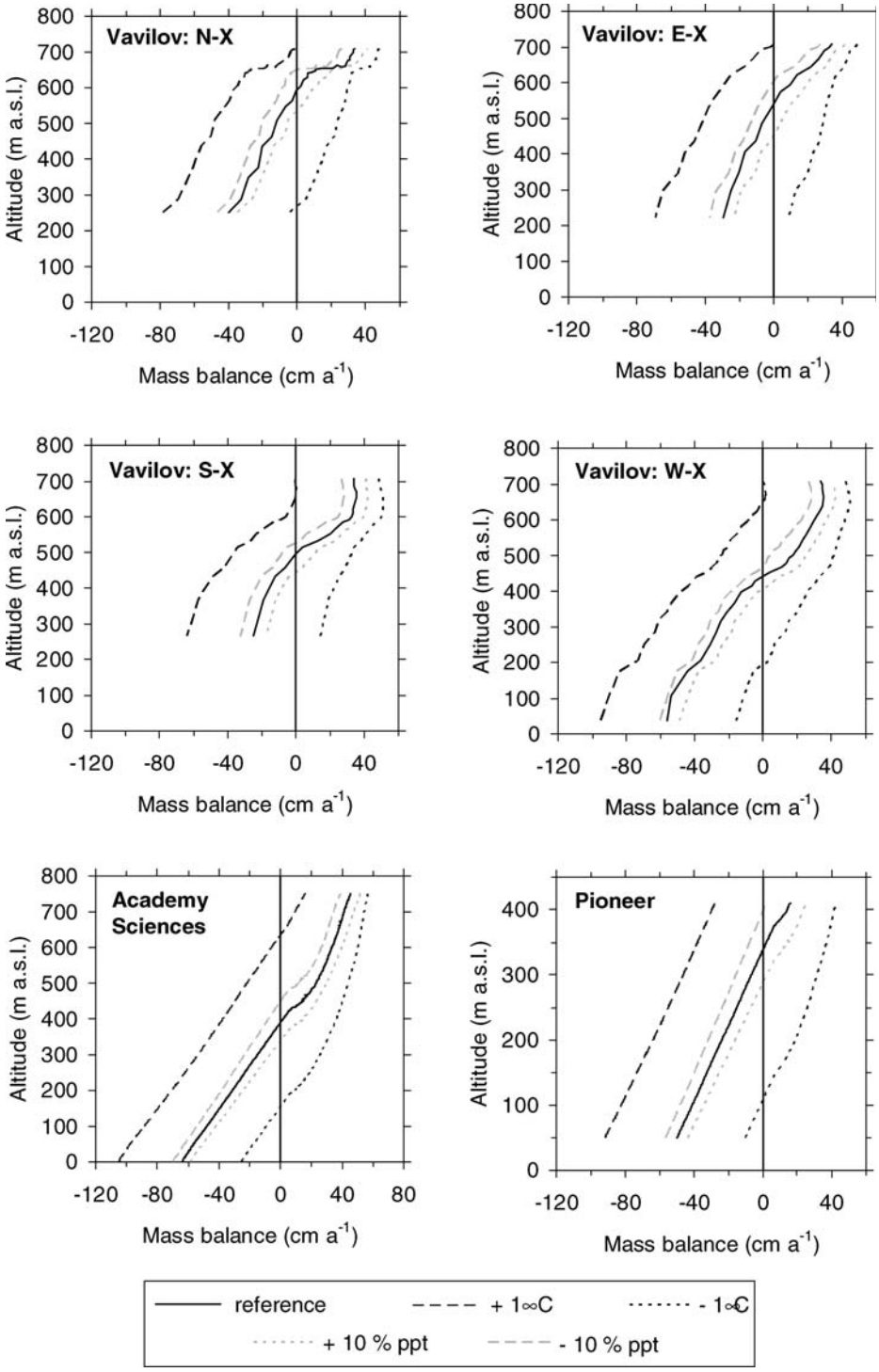



**FIGURE 3. Modeled mass balance profiles of the Vavilov, Academy of Sciences, and Pioneer ice caps for the reference climate, and for changes in temperature and precipitation of ±1°C and ± 10%, respectively. Four profiles are shown for the Vavilov Ice Cap because the relation between simulated mass balance and altitude varies over the ice cap. The variation in mass balance along these profiles is not as smooth as for the other ice caps because the model was calibrated with field measurements showing the same pattern of variation. The profiles for the Vavilov Ice Cap are located in Figure 2b.**

increasingly restricted to the summer months as the climatic setting becomes progressively drier.

## Dynamic Sensitivity of Ice Caps

Simulating the dynamic response of an ice cap to climate change requires the use of a fully coupled mass balance and ice-flow model. This ensures that the effects of changes in ice cap geometry on mass balance are accounted for, unlike the fixed geometry approach used to calculate the static sensitivity. However, dynamic models require input data which are only available for a small number of ice caps and glaciers, restricting the widespread application of such models. Examining a range of individual glaciers and ice caps in different climatic settings should improve our understanding of how to generalize results to a broader scale. Oerlemans et al. (1998) define the dynamic sensitivity to temperature of an ice mass $D_T$ by

$$D_T(t) = \frac{V(t) - V(t_0)}{A(t_0)(t - t_0)\bar{T}'}, \tag{9}$$

where $V$ and $A$ are the volume and area of the ice mass, respectively. $\bar{T}'$ is the mean change in temperature over the time period $(t - t_0)$.

To investigate the variation in dynamic sensitivity of ice masses in different climatic settings, Oerlemans et al. (1998) compared the



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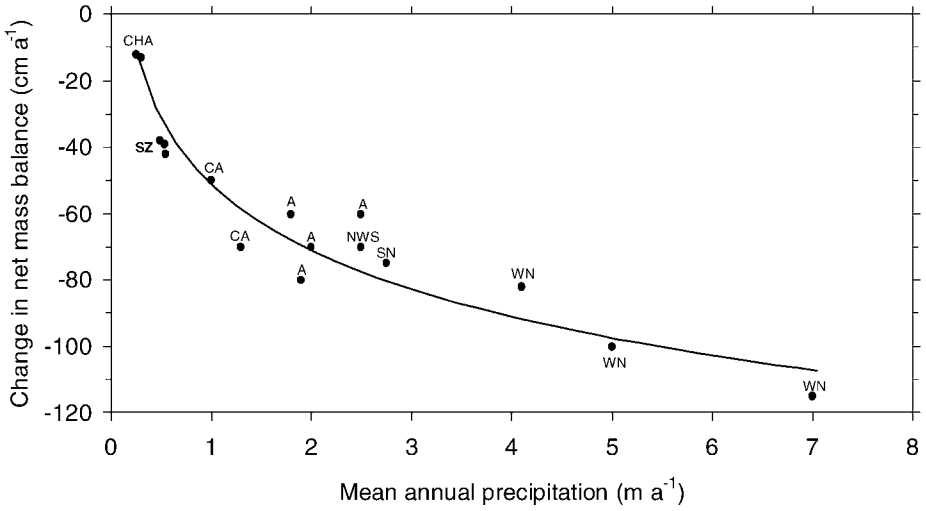



**FIGURE 4. Change in modeled mean net mass balance in response to a 1°C climate warming plotted against mean annual precipitation for a selection of glaciers in various climatic regimes. The three ice caps on Severnaya Zemlya (SZ) are compared to glaciers in the western and drier parts of southern Norway (WN and SN), the Alps (A), northwest Spitsbergen (NWS), central Asia (CA), and the Canadian Arctic (CHA). Data are from Oerlemans and Fortuin (1992) and Fleming et al. (1997). The line is a logarithmic fit used by Oerlemans and Fortuin (1992) to estimate the sensitivity of glacier mass balance to a 1°C climate warming as a function of the mean annual precipitation.**

response of 12 glaciers and small ice caps from across the globe to a set of future climate change scenarios. Details of these ice masses are given in Table 6. Six climate change scenarios were considered by using constant warming rates of 0.01, 0.02, and 0.04°C $a^{-1}$ for the period 1990–2100, repeated with an accompanying change in precipitation of 10% per degree of warming. Initial conditions in each simulation were taken as the mean climate over the reference period 1961–1990.

In order to examine the dynamic sensitivity of ice caps in Severnaya Zemlya, the same series of experiments was performed on the Vavilov and Pioneer ice caps using the coupled mass balance and ice-flow model described in Bassford et al. (2006a, 2006b) and applied to the Vavilov Ice Cap in Bassford et al. (2006b). This is particularly worthwhile because, as Oerlemans et al. (1998) acknowledge, the sample of glaciers used in their study does not represent the dry subpolar glaciers. An attempt was not made to simulate the dynamic sensitivity of the Academy of Sciences Ice Cap, because this ice cap has a relatively complicated flow structure, including fast-flowing ice streams (see Dowdeswell et al., 2002), which is beyond the capability of the ice-flow model. The initial conditions in the six climate change experiments were set to the reference states. An additional simulation was performed in which conditions remained the same as in the reference climate, i.e., no climate warming.

### *THE 1990–2100 SIMULATIONS*

Figure 7 shows changes in the ELA, area, and volume of the Vavilov and Pioneer ice caps in response to the six climate change scenarios, together with results for the simulation in which conditions were unchanged from the reference climate. The range of different responses is large for both ice caps, reflecting their sensitivity to climate change. By the year 2100, the model predicts that the Vavilov Ice Cap would lose 9%, 18%, and 33% of its volume in response to the 0.01, 0.02, and 0.04°C $a^{-1}$ warming scenarios, with a corresponding reduction in area of 2%, 5%, and 11%. In the case of no climate change, the geometry of Vavilov Ice Cap hardly changes, with a slight decrease in volume and area of $<1\%$. For Pioneer Ice Cap, the changes in normalized volume are considerably larger. In fact, the ice cap loses 37%, 50%, and 71% of its volume by 2100 for the 0.01, 0.02 and 0.04°C $a^{-1}$ warming rates. Even if the conditions remain the same as the reference climate, the model still calculates a 22% reduction in ice cap volume over the 110 year period. An interesting difference between the dynamic response of the two ice caps is the way in which their area changes over time (Fig. 7). The rate of the decrease in area of Vavilov Ice Cap gradually increases as temperature continues to rise, while the margins of Pioneer Ice Cap retreat rapidly before its area continues to decrease at a more gradual rate. The latter results from a rapid melting of thin and stagnant ice, particularly in the area close to the northern and eastern margins, followed by a slower retreat of dynamically active margins.

The effect of an increase in precipitation is to effectively reduce the *loss* of ice volume, but the change in precipitation of 10% $°C^{-1}$ is not nearly enough to compensate for the increase in surface melting due to a rise in temperature (Fig. 7). Much larger increases in precipitation would be required to maintain mass balance in a warmer climate. A significant result of these experiments is that the ELA exceeds the summit of Pioneer Ice Cap by 2100 in all of the climate change scenarios, which would lead to the complete wastage of the ice cap. This is also the case in the 0.02 and 0.04°C $a^{-1}$ warming scenarios for Vavilov Ice Cap, although the rate of its wastage would be much lower than for Pioneer Ice Cap.

### *COMPARISON OF STATIC AND DYNAMIC SENSITIVITIES FOR A SELECTION OF ICE MASSES*

Equation 9 was used to calculate the dynamic sensitivity of the Vavilov and Pioneer ice caps for the 0.02°C $a^{-1}$ scenario using two time periods, 1990–2050 and 1990–2100. The results are shown in Figure 8, together with the static sensitivities calculated by Bassford et al. (2006b) and the results presented by Oerlemans et al. (1998) for the sample of ice masses listed in Table 6. While the static sensitivities of the Vavilov and Pioneer ice caps are relatively low on a global scale, their dynamic sensitivities are comparable with Alpine and Scandinavian glaciers. The key factor responsible for this is the faster response times of temperate glaciers, which adjust their geometry more quickly to climate change. It is noteworthy that the dynamic sensitivity of the Vavilov and Pioneer ice caps is slightly higher than the static sensitivity. This is explained by the altitude–mass balance feedback whereby increased melting leads to a lowering in ice surface elevation which in turn results in a more negative mass balance. The feedback is particularly strong for the Vavilov and Pioneer ice caps because they have long response times to climate change, resulting in a high rate of surface lowering relative to the reduction in area of the ablation zone resulting from retreat of the ice cap margins.



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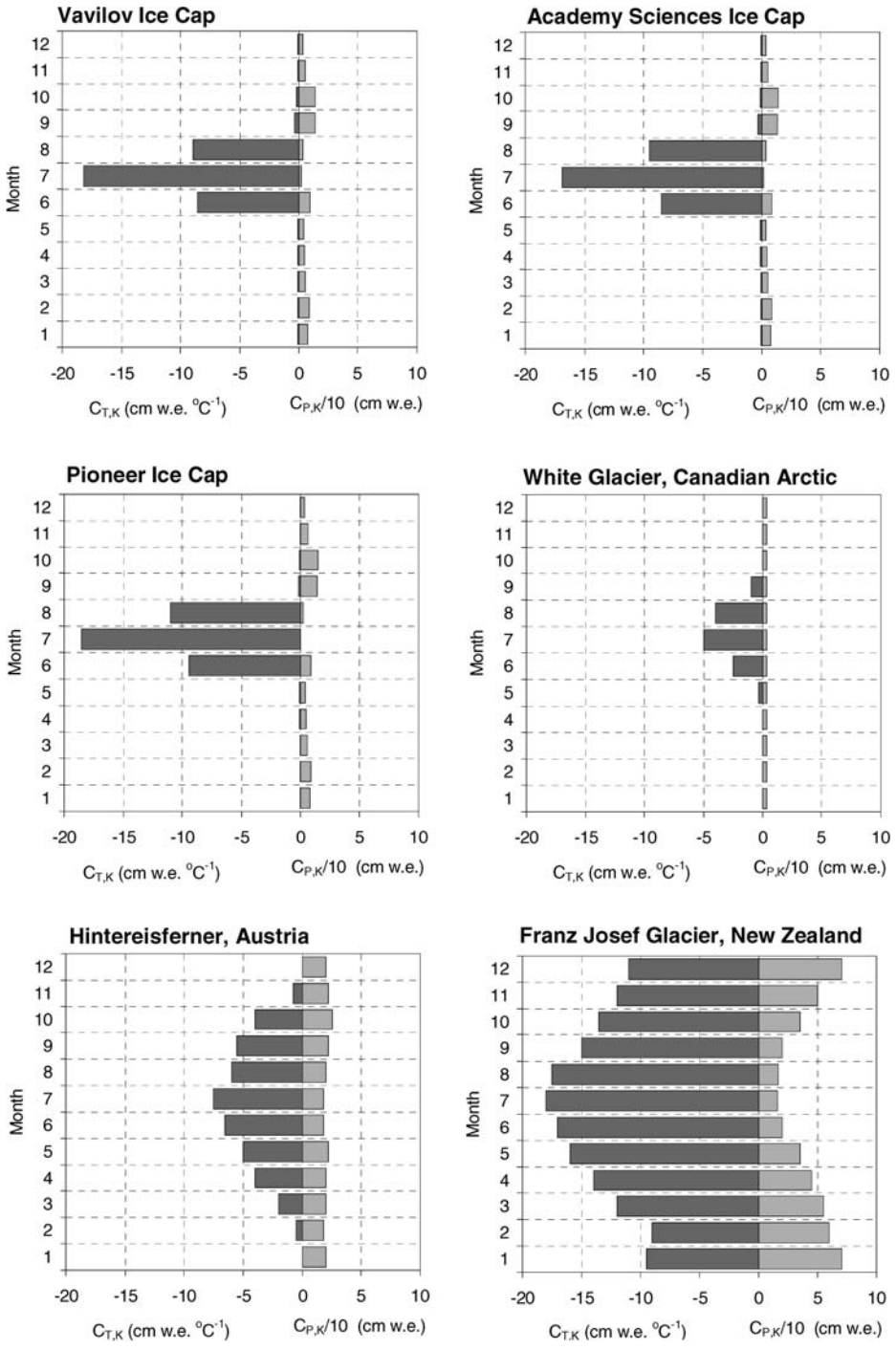



**FIGURE 5. Seasonal sensitivity characteristic for Vavilov, Academy of Sciences, and Pioneer ice caps calculated with the mass balance model, shown together with results from Oerlemans and Reichert (2000) for a selection of glaciers in various climatic regimes. Note that the calendar for Franz Josef Glacier, which is located in the southern hemisphere, has been shifted by 6 months to make it comparable with the other glaciers.**

A noticeable result is that the dynamic sensitivity of Pioneer Ice Cap is particularly high for the period 1990–2050, $D_T = 85$ cm w.e. a$^{-1}$ °C$^{-1}$, but falls to a moderate value of $D_T = 51$ cm w.e. a$^{-1}$ °C$^{-1}$ for the period 1990–2100. This reflects the fact that the Pioneer Ice Cap is much larger than the equilibrium size for the initial climatic conditions. The rapid retreat of the ice cap between the years 2030 and 2050 has the effect of reducing the size of the ablation area, which decreases the rate of mass loss resulting in a lower dynamic sensitivity for the period 1990–2100. The simulated retreat of the Pioneer Ice Cap is consistent with a measured reduction in area of ~20%, based on the difference between Russian inventory data, probably representing the state of the ice cap in the 1950s, with the area derived from a Landsat image acquired in 1988 (M. Williams, personal communication). In addition, comparison of aerial photographs and maps indicate that the area of the ice cap decreased by 27.3 km$^2$, or about 14% of the current area, in the period 1931–1953 (Kislov and Koryakin, 1986). Therefore, observations show that the Pioneer Ice Cap has been retreating for at least 70 years and model results predict that the ice cap will continue to decrease in size throughout the 21st century, unless future climatic conditions become cooler or considerably wetter.

Figure 9 shows the change in volume of the Vavilov and Pioneer ice caps over the period 1990–2100 for the 0.02°C a$^{-1}$ warming scenario, alongside results presented by Oerlemans et al. (1998) for the sample of 12 ice masses. Despite its relatively small fractional loss in volume (Fig. 7), the Vavilov Ice Cap dominates the total volume of ice wastage from the sample of ice masses, reflecting the much greater size of this ice cap (Table 6). Although the absolute loss in the volume of the Pioneer Ice Cap is only about 10% of that for the Vavilov Ice Cap,



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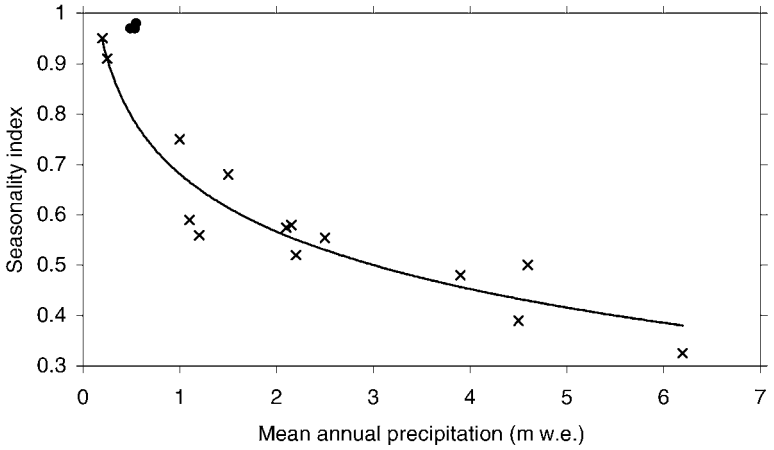



**FIGURE 6. The seasonality index plotted against mean annual precipitation for Vavilov, Academy of Sciences, and Pioneer ice caps (filled circles) together with data from Oerlemans and Reichert (2000) for a sample of 14 glaciers in various climatic regimes (crosses). The line is a logarithmic fit to the results of Oerlemans and Reichert (2000).**

it still exceeds the total ice wastage from all of the glaciers in the sample, excluding Blondujökull, the KGI Ice Cap, and Illvidrajökull.

### *SIMULATION WITH A REGIONAL AND SEASONAL CLIMATE CHANGE SCENARIO*

A model simulation was performed using a future climate change scenario specific to Severnaya Zemlya. The objective of this simulation was to determine the most realistic assessment of the response of the Vavilov and Pioneer ice caps to future climate change. The simulation used a climate change scenario determined by the HadCM3 coupled atmospheric-ocean general circulation model (AOGCM), developed by the Hadley Centre (Pope et al., 2000). The climate projection follows the IS92a "business as usual" scenario, in which the atmospheric concentration of carbon dioxide more than doubles over the course of the 21st Century. Table 7 lists the seasonal changes in temperature and precipitation specified in this scenario. The scenario was imposed on the reference climate assuming a linear change in temperature and precipitation over the period 1990–2100, after which the climate was held constant. The coupled mass balance and ice-flow model was run forward in time for 2000 years, or until the ice cap had wasted away completely.

The response of the Vavilov and Pioneer ice caps to the IS92a "business as usual" scenario is dramatic (Fig. 10). By 2013, the ELA exceeds the summit of Pioneer Ice Cap, at which point the ablation zone covers the entire ice cap, leading to a rapid loss of ice and the complete wastage of the ice cap by 2370 (i.e., in about 370 years). Under a fixed reference climate, the reduction in volume is more gradual, but the ice cap still disappears eventually in 3367, i.e., 1377 years after the start of the simulation in 1990. In the case of the Vavilov Ice Cap, the ELA ascends from 498 m a.s.l. to 627 m a.s.l. by the time climate stabilizes in year 2100, leaving a small accumulation zone at the summit of the ice cap. However, a lowering of the ice surface in the accumulation zone due to the flux of ice into the ablation zone causes the ELA to rise above the summit of the ice cap by the year 2160. Subsequent melting, intensified by the altitude-mass balance feedback, causes the Vavilov Ice Cap to disappear entirely by the year 3073, i.e., 1083 years after the start of the simulation.

A key factor in the predicted wastage of the Vavilov and Pioneer ice caps is their hypsometry, which is characterized by a small altitudinal range close to sea level, with the majority of the accumulation zone lying $<$200 m above the ELA. Consequently, a relatively small rise in summer temperature shifts a large part of the accumulation zone into the ablation zone. Since both these ice caps rest on relatively flat beds close to sea level, they cannot retreat to higher ground, which would support glaciation in a warmer climate. This is also true for most of the other ice caps in Severnaya Zemlya (Dowdeswell et al., in press), which can be expected to respond in a similar way to the Vavilov and Pioneer ice caps. Therefore, despite having a relatively low static sensitivity, the Vavilov and Pioneer ice caps are highly susceptible to long term climate change due to their regional topographic setting. If the ice caps on Severnaya respond to future climate in the way predicted by the model, global sea level will rise as a consequence by a few centimeters.

### *GLOBAL CHANGES IN ICE VOLUME*

Oerlemans et al. (1998) combined the response of 12 ice masses to a 0.02°C $a^{-1}$ warming scenario in order to calculate the overall change in normalized ice volume of a sample of glaciers and ice caps (Table 6). The rationale behind this was to develop a simplified scheme which represents the global response of ice masses to climate change. Two methods were used, based on (1) the mean of the normalized change in volume of the individual ice masses, so that each glacier and ice cap has an equal weighting, and (2) the total change in volume of the 12 ice masses used scaled with the total volume in 1990. The latter is dominated by changes in the large ice masses, such as King George Island Ice Cap, Illvidrajökull, and Blondujökull (Table 6). Oerlemans et al. (1998) refer to the quantities calculated using the first and second methods as $\langle V_{sc} \rangle$ and $\langle V \rangle_{sc}$, respectively.

**TABLE 6**

**Glaciers and ice caps studied by Oerlemans et al. (1998). KGI Ice Cap is King George Island Ice Cap located off the Antarctic Peninsula. Details for the Vavilov and Pioneer ice caps are shown for comparison.**

| Glacier/ice cap | Location | Area ($km^2$) | Volume ($km^3$) | ELA (m a.s.l.) |
|---|---|---|---|---|
| Franz Josef Glacier | New Zealand | 34 | 4.89 | 1650 |
| Glacier d'Argentière | France | 15.6 | 1.91 | 2900 |
| Haut Glacier d'Arolla | Switzerland | 6.3 | 0.33 | 3200 |
| Hintereisferner | Austria | 7.4 | 0.44 | 2950 |
| Nigardsbreen | Norway | 48 | 3.80 | 1550 |
| Pasterze | Austria | 19.8 | 2.62 | 2880 |
| Rhonegletscher | Switzerland | 17.7 | 2.58 | 2930 |
| Storglaciären | Sweden | 3.1 | 0.30 | 1460 |
| Unt. Grindelwaldgletscher | Switzerland | 21.7 | 1.83 | 2770 |
| Blondujökull | Iceland | 226 | 46.9 | 1300 |
| Illvidrajökull | Iceland | 116 | 25.8 | 1250 |
| KGI Ice Cap | Antarctica | 1402 | 155 | 100 |
| Vavilov Ice Cap | Severnaya Zemlya | 1772 | 567 | 498 |
| Pioneer Ice Cap | Severnaya Zemlya | 200 | 25 | 350 |



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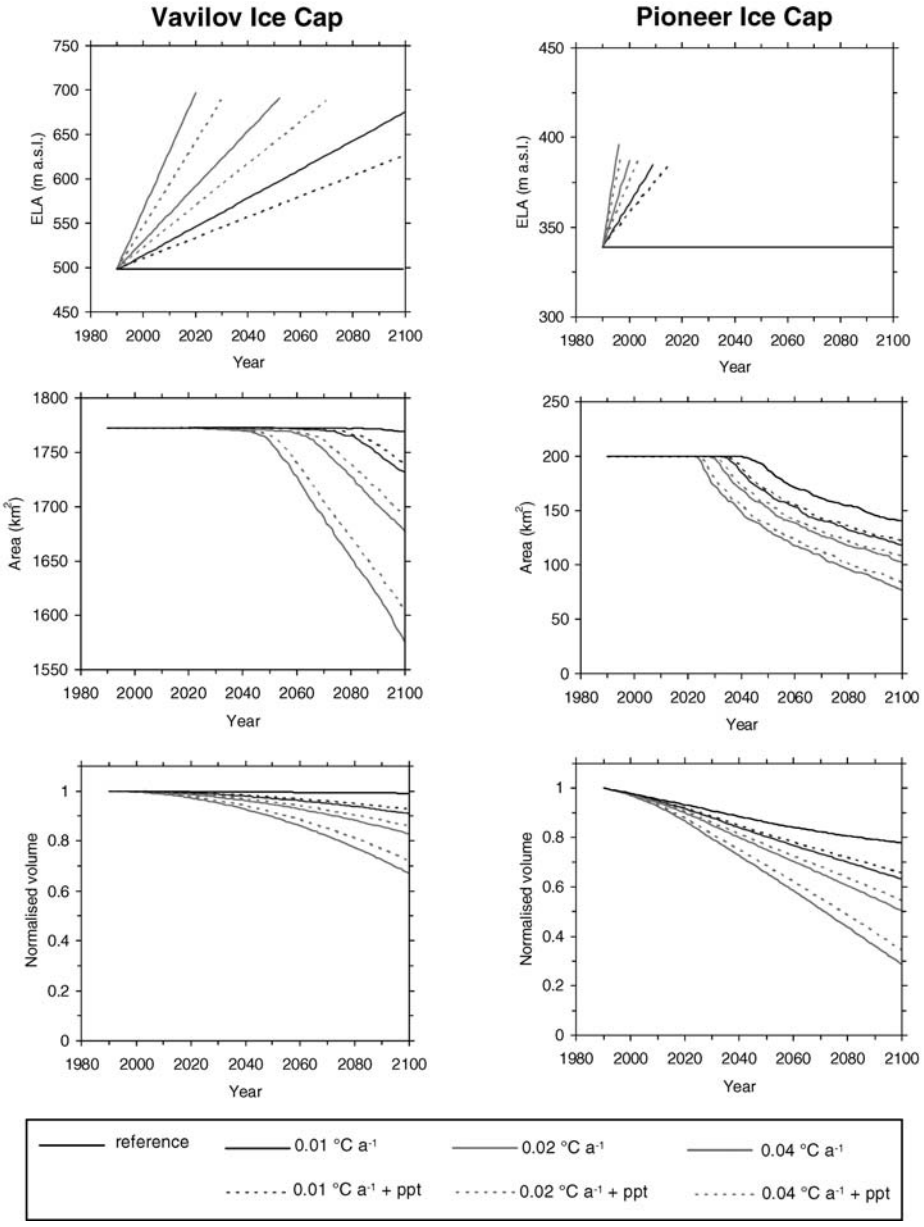



**FIGURE 7. Changes in the mean equilibrium line altitude (ELA), area, and volume of the Vavilov and Pioneer ice caps in response to climate warming scenarios of 0.01, 0.02, and 0.04°C $a^{-1}$. Simulations including a 10% increase in precipitation per degree of warming are also shown, referred to as + ppt in the key, along with a simulation in which conditions remained the same as the reference climate. Ice cap volume is normalized relative to the 1990 volume. Changes in the ELA are shown until the ELA exceeds the transient maximum elevation of the ice cap. It appears that the area of the ice caps remains constant for about 30 years before decreasing. This is an artifact of the relatively large grid cell size used in the model. Cells at the ice cap margins have an initial ice thickness of ~50 m which takes time to melt away completely, resulting in an area change.**

Figure 11 shows $\langle V_{sc} \rangle$ and $\langle V \rangle_{sc}$ for the period 1990–2100, together with the normalized change in volume of the Vavilov and Pioneer ice caps. Also shown are results produced by the fixed geometry approach (FG), including changes in the volume of the Academy of Sciences Ice Cap. The errors involved in using the fixed geometry approach for the Vavilov and Pioneer ice caps are relatively small compared with those in the calculation of $\langle V_{sc} \rangle$ and $\langle V \rangle_{sc}$. In fact, for the Vavilov Ice Cap, the difference between the fixed geometry and dynamic calculations is <2%, implying that geometric effects on the mass balance of this ice cap are relatively minor over the time period considered. This reflects the much longer response time of the large subpolar ice caps compared with temperate glaciers. On the basis of the insignificant errors in the fixed geometry results for the Vavilov Ice Cap, greater confidence can be attributed to the calculation for Academy of Sciences Ice Cap. However, this assumption is not valid over longer time periods as geometric effects on mass balance become increasingly important. On a shorter time scale of <100 years, geometric effects become important for smaller ice caps which are currently in a state of relatively rapid retreat, as is the case for the Pioneer Ice Cap (Fig. 11).

In contrast to $\langle V_{sc} \rangle$ and $\langle V \rangle_{sc}$, the fixed geometry approach underestimates the reduction in volume of the Vavilov Ice Cap because of the dominance of the altitude–mass balance feedback over the effect of retreating margins on the size of the ablation area. This questions the assumption made by Oerlemans et al. (1998) and Gregory and Oerlemans (1998) that the fixed geometry approach represents an upper limit for the change in volume of ice masses over the next 100 years.

The reduction in normalized volume of each of the ice caps in Severnaya Zemlya is smaller than the average of the 12 ice masses used in Oerlemans et al. (1998), particularly in the case of the Vavilov and Academy of Sciences ice caps, which are calculated to lose less than 20% of their volume by 2100 for the 0.02°C $a^{-1}$ warming scenario (Fig. 11). Oerlemans et al. (1998) are careful to emphasize that the sample of glaciers and ice caps used in the calculation of $\langle V_{sc} \rangle$ and $\langle V \rangle_{sc}$ is not representative of all ice masses around the world, in particular the dry subpolar ice caps. Under a warmer climate, some of the small subpolar ice caps and glaciers, such as Pioneer Ice Cap, are likely to lose a large proportion of their volume over the next 100 years. However, changes in the total volume of subpolar ice masses



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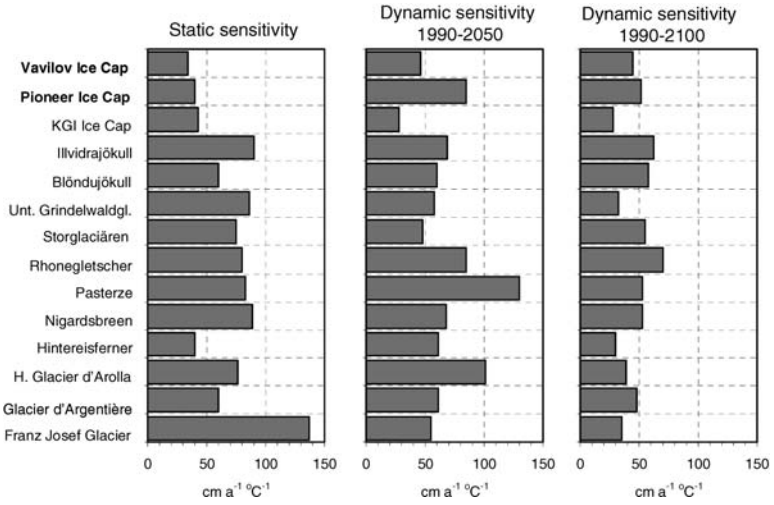



**FIGURE 8. Static and dynamic sensitivity of the Vavilov and Pioneer ice caps to temperature change, together with results from Oerlemans et al. (1998) for 12 other glaciers. The static sensitivity is defined for the 1990 glacier geometries. The dynamic sensitivity was calculated for the 0.02°C $a^{-1}$ scenario for years 2050 and 2100.**

will be dominated by the response of larger ice caps which have a low sensitivity and long response time to climate change, for example, the Vavilov and Academy of Sciences ice caps. Excluding the Greenland and Antarctic ice sheets, High Arctic ice masses such as these represent about 200,000 $km^2$ or approximately 37% of the Earth's total ice cover (Meier, 1984; Warrick and Oerlemans, 1990), and very likely an even greater proportion of the total ice volume. Therefore, as Oerlemans et al. (1998) suggest, including the response of the large subpolar ice caps in a calculation of $\langle V \rangle_{sc}$ would significantly reduce the fractional loss of ice compared to the calculation based on the sample of ice masses biased towards temperate glaciers.

## Summary and Conclusions

A series of model experiments was performed to test the static mass balance sensitivity of the Vavilov, Academy of Sciences, and Pioneer ice caps to climate change. Mean results for the three ice caps indicate a change in net mass balance of –36 cm w.e. $a^{-1}$ $°C^{-1}$ and 1 cm w.e. $a^{-1}$ $\%^{-1}$ for perturbations in temperature and precipitation, with accompanying changes of 219 m $°C^{-1}$ and –6 m $\%^{-1}$ in the equilibrium line altitude. On a global scale, the static sensitivity of the Vavilov, Academy of Sciences, and Pioneer ice caps is quite low, supporting the notion that ice masses located in a dry climate are less sensitive to climate change. The seasonal sensitivity characteristic, calculated for each of the three ice caps, indicates that the sensitivity of mass balance to small perturbations in temperature (±1°C) is determined almost entirely by the summer months (June, July, and August), while changes during the rest of the year have a negligible effect because temperatures remain well below the melting point.

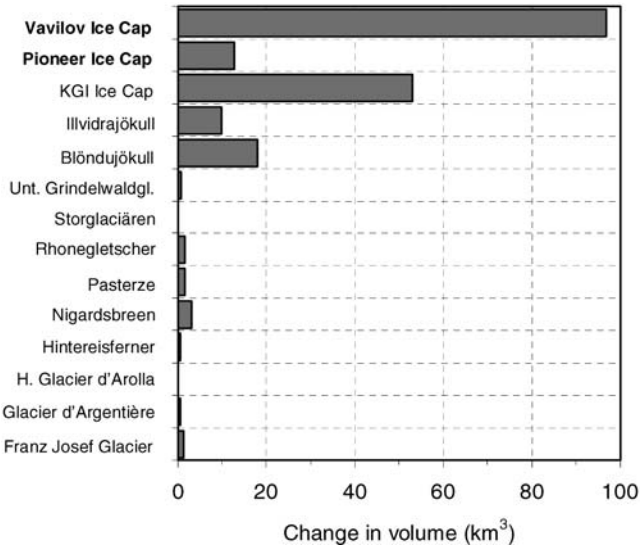



**FIGURE 9. Absolute change in the volume of Vavilov and Pioneer ice caps in response to a climate warming of 0.02°C $a^{-1}$, shown together with results from Oerlemans et al. (1998) for 12 other glaciers (see Table 6 for details). Data is the difference between the 1990 and 2100 volumes.**

The dynamic responses of the Vavilov and Pioneer ice caps to a range of future climate warming scenarios were simulated using a coupled mass balance and ice-flow model. Modeling predicts that the Vavilov Ice Cap would lose 9%, 18%, and 33% of its 1990 volume by the year 2100 in response to climate warming of 0.01, 0.02, and 0.04°C $a^{-1}$, with a corresponding reduction in area of 2%, 5%, and 11%. For the Pioneer Ice Cap the changes in normalized volume are considerably greater because this ice cap is already in a state of strong negative mass balance under the reference climate. In fact, this ice cap is predicted to lose 37%, 50%, and 71% of its volume by 2100 for the 0.01, 0.02, and 0.04°C $a^{-1}$ warming rates. The effect of an increase in precipitation is to reduce the loss of ice volume, but a change in precipitation of 10% per degree of warming is not nearly enough to compensate for the increase in surface melting due to a rise in temperature. Under a future climate change scenario specific to Severnaya Zemlya, the model predicts that the Vavilov Ice Cap will completely waste away by the year 3073, i.e., 1083 years after the start of the simulation in 1990, while the Pioneer Ice Cap will disappear by 2160. Despite having a low static sensitivity, these ice caps are highly susceptible to long term climate change because of their hypsometry and the fact that they rest on relatively flat beds close to sea level. Although it is difficult to say with certainty the exact rate of decay, given the volumes of ice

**TABLE 7**

**Seasonal changes in temperature and precipitation determined by the HadCM3 AOGCM for the IS92a "business as usual" scenario (Pope et al., 2000). Changes are shown both for the annual average and for each of the four seasons, December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). The changes in precipitation are equivalent to an increase of 73 mm in the annual total, or an increase of 17% compared to the reference climate.**

| Climate variable | DJF | MAM | JJA | SON | Mean |
|---|---|---|---|---|---|
| Temperature (°C) | 12.4 | 4.8 | 1.2 | 5.5 | 6.0 |
| Precipitation (mm $day^{-1}$) | 0.31 | 0.12 | 0.17 | 0.21 | 0.20 |



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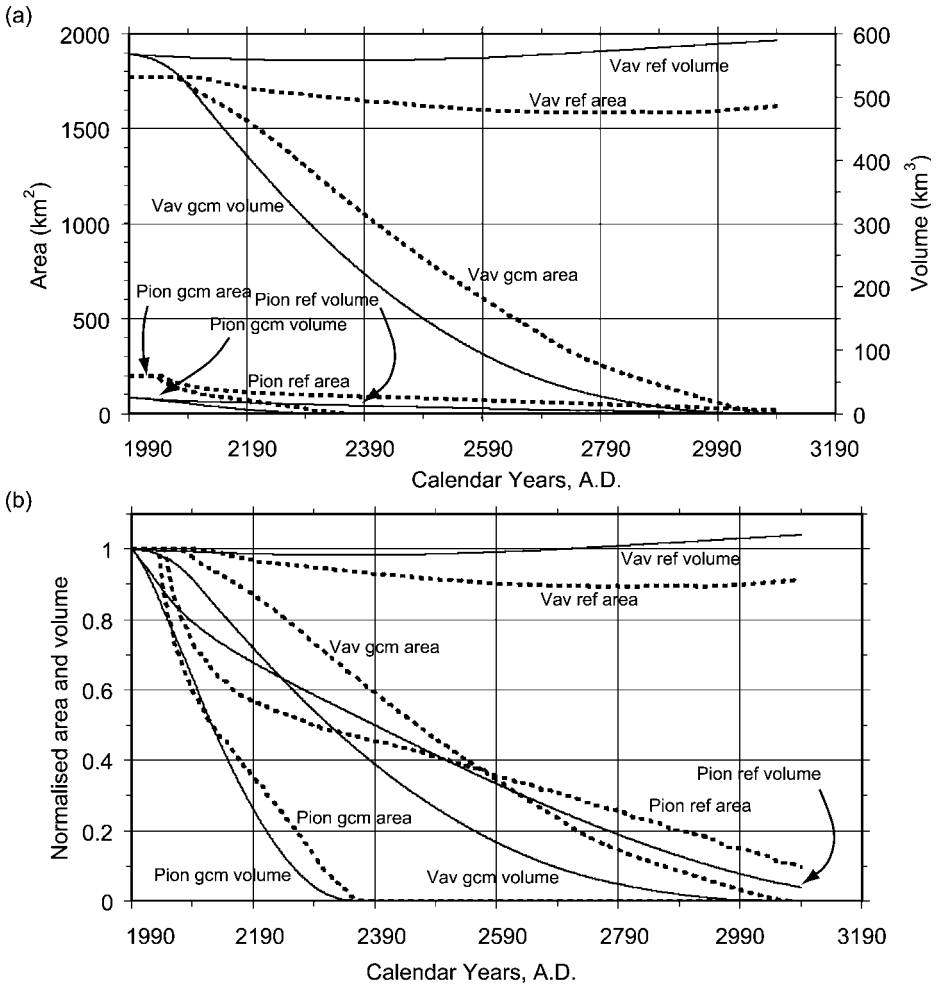



**FIGURE 10. Projected change in area and volume of the Vavilov and Pioneer ice caps in response to a regional and seasonal climate change scenario for Severnaya Zemlya, together with results for a constant reference climate. Vav and Pion refer to the Vavilov and Pioneer ice caps, while gcm and ref denote results for the climate change scenario and the reference climate, respectively. Changes in actual and normalized area and volume are shown.**

determined by Dowdeswell et al. (2002) for Severnaya Zemlya, it is likely that ice loss from these islands will contribute, over a period of a few hundred years, a rise in sea level of the order of a few centimeters.

Changes in the normalized volume of the Vavilov Ice Cap between 1990 and 2100 calculated using the fixed geometry approach were found to be within 2% of the results obtained using the dynamic model. This suggests that for large ice caps geometric effects on the mass balance are relatively minor over a time period of 100 years or so. However, this assumption is not valid for smaller ice caps, such as the Pioneer Ice Cap, and glaciers which have a much faster response time to climate change. The reduction in normalized volume calculated for the ice caps in Severnaya Zemlya is smaller than the average for a sample of 12 ice masses examined by Oerlemans et al. (1998), especially in the case of the Vavilov and Academy of Sciences ice caps. Large ice caps such as these, which have a low sensitivity and

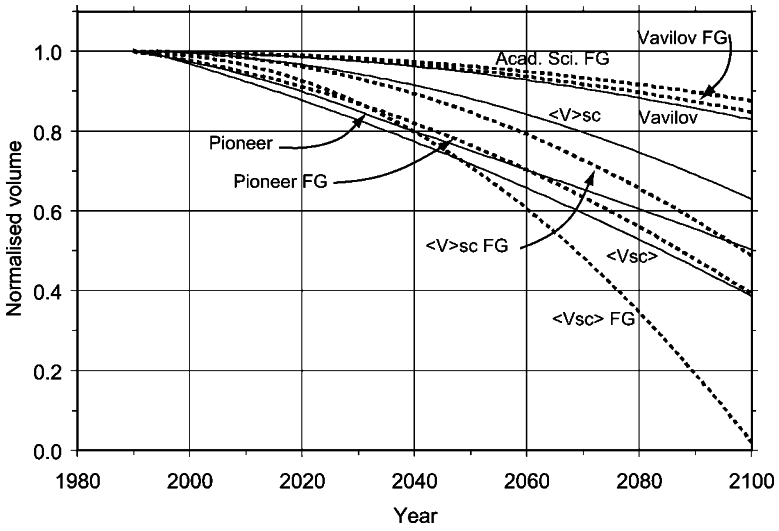



**FIGURE 11. Change in normalized volume of the Vavilov, Academy of Sciences, and Pioneer ice caps in response to climate warming of 0.02°C a$^{-1}$, calculated using the dynamic and fixed geometry (FG) approaches, shown with results from Oerlemans et al. (1998) of the scaled response of a sample of 12 glaciers and ice caps. See text for explanations of $\langle V \rangle_{sc}$ and $\langle V_{sc} \rangle$. The dynamic response of the Academy of Sciences Ice Cap was not calculated.**



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a long response time to climate change, will dominate changes in the total volume of High Arctic ice masses and should, therefore, be represented in any generalized scheme designed to predict changes in global ice volume.

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