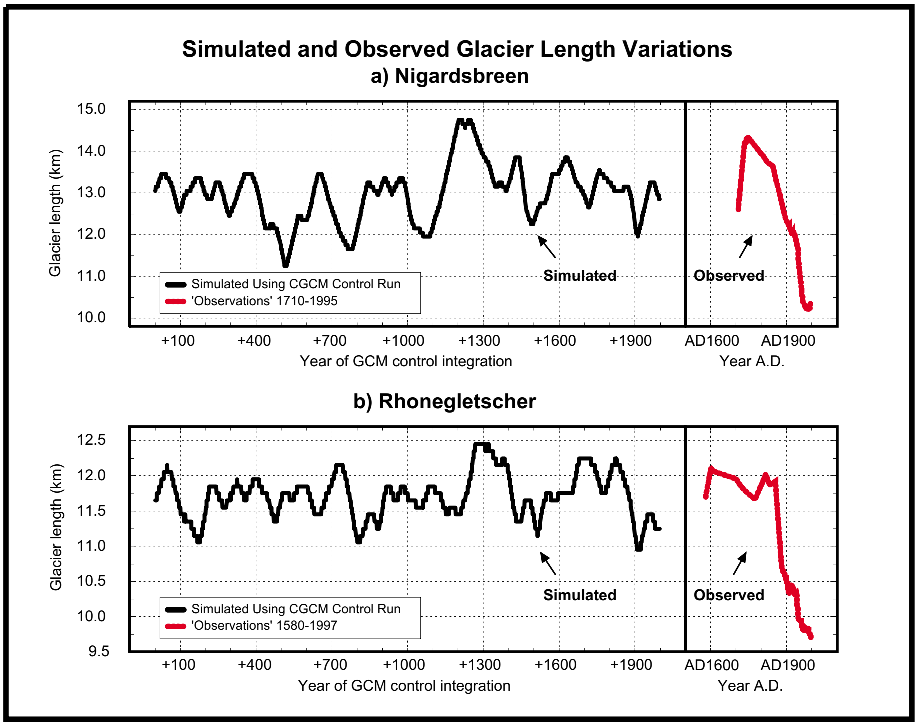
Max-Planck-Institut für Meteorologie

REPORT No. 328



NATURAL CLIMATE VARIABILITY AS INDICATED BY GLACIERS AND IMPLICATIONS FOR CLIMATE CHANGE: A MODELING STUDY

by

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HAMBURG, August 2001

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REPb 328

Natural Climate Variability as Indicated by Glaciers and Implications for Climate Change: A Modeling Study

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submitted to
Journal of Climate

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ABSTRACT

Glacier fluctuations exclusively due to internal variations in the climate system are simulated using downscaled integrations of the ECHAM4/OPYC coupled general circulation model (GCM). A process-based modeling approach using a mass balance model of intermediate complexity and a dynamic ice flow model considering simple shearing flow and sliding are applied. Multi-millennia records of glacier length fluctuations for Nigardsbreen (Norway) and Rhonegletscher (Switzerland) are simulated using auto-regressive processes determined by statistically downscaled GCM experiments. Return periods and probabilities of specific glacier length changes using GCM integrations excluding external forcings such as solar irradiation changes, volcanic or anthropogenic effects are analyzed and compared to historical glacier length records. Preindustrial fluctuations of the glaciers as far as observed or reconstructed, including their advance during the "Little Ice Age", can be explained by internal variability in the climate system as represented by a GCM. However, fluctuations comparable to the present-day glacier retreat do not occur in the GCM control experiments and must be caused by external forcing, with anthropogenic forcing being a likely candidate.

1. Introduction

Quantifying natural climate variability and understanding the underlying physical mechanisms are major scientific goals of current climate research, also with respect to the investigation of anthropogenic impacts on climate. What are the possible physical processes responsible for preindustrial climatic variations over the past millennium such as the "Medieval Warm Period" or the "Little Ice Age" (Grove 1988) lasting for decades or centuries (Bengtsson and Reichert 2000)? Volcanic activity effects the global climate (Hansen et al. 1992; Lindzen and Giannitsis 1998), but only a series of major eruptions are likely to cool global temperature on decadal or longer time scales. Estimations of variability in solar irradiation (Lean et al. 1995; Hoyt and Schatten 1993) are based on indirect and fragmentary evidence but may explain global temperature changes at a level of a few tenths of a degree (Cubasch et al. 1997). However, it appears that a dominant part of climatic variability over the past millennium may be explained by internal variability in the climate system. Hasselmann (1976) demonstrated that low-frequency variations in a system such as the climate could simply be the integrated response of a linear (or nonlinear) system forced by short-term variations resulting, for example, from the macroturbulent atmospheric flow at midlatitudes. The dynamics of a physical system can turn short-term stochastic forcing into low-frequency climate variability. This has been demonstrated using ocean general circulation models (Mikolajewicz and Maier-Reimer 1990) and is also applicable to the dynamic response of glacier systems (Paterson 1994) as investigated in this study. Other possible mechanisms inherent to the climate system are internal ocean variability, ENSO variability and other coupled atmosphere-ocean modes (Sarachik et al. 1996; Bengtsson and Reichert 2000; Bengtsson 2001).

General circulation models (GCMs) integrated over long periods of time are essential tools in investigating the role of forcing factors. As an example, it is investigated in this study to what extent fluctuations of specific glaciers, as far as observed or reconstructed both prior to industrialization and within the 20th century, can be explained by internal climate variations as simulated by a coupled GCM. External forcings such as solar irradiation changes, volcanic or anthropogenic effects are excluded in the GCM experiments.

Glacier fluctuations result from changes in the mass and energy balance at the earth's surface and represent valuable paleoclimatic proxy data providing important information on climate variability over long periods of time. They are also key elements for the early detection of climate change and possible anthropogenic impacts on climate. Changes in glacier mass balance (defined as the annual mass gain or loss at the surface of a glacier; Paterson 1994) can be viewed as the direct reaction of a glacier to climatic variations without delay. Mass balance variations are mainly sensitive to the seasonal distributions of both temperature and precipitation, with sensitivities varying enormously among individual glaciers. For the maritime glacier Nigardsbreen (Norway), it has, for example, been shown (Reichert et al. 2001) that a 1ºC higher temperature in summer (Jun, Jul, Aug) can have the same effect on mass balance as 20% less precipitation in winter (Dec, Jan, Feb). The process-based modeling approach applied in this study (Figure 1) accounts for these strongly varying seasonally-dependant sensitivity characteristics for individual glaciers (section 2).

Variations in glacier length are the indirect, delayed, filtered, and strongly enhanced response to climatic variations and are therefore much more difficult to interpret than glacier mass balance. However, the available records of observed or reconstructed historic glacier length fluctuations are much longer (often multi-centennial) than available mass balance records (usually less than 50 years). In order to be able to compare these long glacier length records to modeling studies, a dynamic ice flow model calculating the response of glacier geometry (including the position of the glacier front) to changes in specific mass balance is used in this study (section 3). We simulate specific glacier length fluctuations for the temperate valley glaciers Nigardsbreen (Norway; 61º43'N, 7º08'E) and Rhonegletscher (Swiss Alps; 46º37'N, 8º24'E) for comparison with historical records of glacier length (section 5). In order to simulate long, statistically significant records of low frequency glacier length fluctuations, we introduce a method using auto-regressive processes to generate multi-millennia records of mass balance from temporally limited GCM integrations (section 4). We investigate the probability that preindustrial glacier length variations can be explained by internal fluctuations inherent to the climate and the glacier system. We furthermore examine whether it is likely that the general retreat of the glaciers observed during the 20th century, may be explained by internal variations as simulated by a GCM or whether additional external forcing, such as anthropogenic forcing, is required (section 6 and 7).

2. GCM experiments and simulation of mass balance

We use statistically downscaled integrations of the European Center/Hamburg coupled general circulation model ECHAM4/OPYC (Roeckner et al. 1996; 1999) thereby extending studies assuming purely white-noise climatic forcing (Oerlemans, 2000; 2001). The atmospheric model ECHAM4 has 19 levels in the vertical extending up to 10 hPa. It is coupled to the full ocean general circulation model OPYC (Oberhuber 1993) consisting of three sub-models for the interior ocean, for the surface mixed-layer, and for sea ice (dynamic-thermodynamic sea ice model including viscous plastic rheology). The control integration used in this study has been integrated at T42 resolution (corresponding to a latitude-longitude grid of about 2.8° x 2.8°) excluding any external forcing such as solar irradiation changes, volcanic or anthropogenic effects. The concentrations of carbon dioxide, methane, and nitrous oxide are fixed at the observed 1990 values [Intergovernmental Panel on Climate Change (IPCC) 1990, their Table 2.5]. After a 100-year spinup, the model has been integrated with constant flux adjustment for 300 years (Roeckner et al. 1999). Statistical downscaling of GCM integrations is based on daily reanalyses of the European Centre for Medium-Range Weather Forecasts (ECMWF; Gibson et al. 1997) and weather station data in the vicinity of the investigated glaciers, a detailed description of the method can be found in Reichert et al. (1999).

A process-based modeling approach using a mass balance model of intermediate complexity (Oerlemans 1992) and glacier specific seasonal sensitivity characteristics (SSCs; Oerlemans and Reichert 2000) is applied in order to simulate glacier mass balance for Nigardsbreen and Rhonegletscher. The SSCs represent the dependence of mass balance on monthly perturbations in temperature and precipitation and have been calculated from the process-based mass balance model, individually for each glacier.

The SSCs for Nigardsbreen and Rhonegletscher are shown in Figure 2. For the maritime glacier Nigardsbreen (Figure 2a), the melt season especially on the lower parts of the glacier is long, the sensitivity to changes in temperature is high from May to October. Temperature anomalies during these months lead to a strong response in mass balance whereas temperature changes in winter (December to February) have almost no effect since melting hardly occurs. The sensitivity of mass balance to relative changes in precipitation is very low in summer (June to August) since summer precipitation falls as rain over most parts of the glacier. In winter, precipitation mainly falls as snow and can be added to the surface naturally leading to a strong effect on the annual mass balance.

Since the accumulation area of Rhonegletscher (Figure 2b) is located at higher altitudes (2140 m to 3620 m) compared to Nigardsbreen (295 m to 1950 m), lower annual air temperatures at the equilibrium line of the glacier (characterizing the glacier in its climatic and topographic setting) lead to a considerable effect also of summer precipitation (with a large fraction falling as snow at these altitudes). The sensitivity is in fact almost constant over the entire year. With respect to changes in monthly temperature, Rhonegletscher is generally less sensitive than Nigardsbreen.

Further details on the mass balance model, individual simulations using the SSCs, model validation using ECMWF reanalyses, and the impact of the North Atlantic Oscillation (NAO) on mass balance fluctuations of Nigardsbreen and Rhonegletscher are provided in Reichert et al. (2001).

3. The ice flow model

In order to be able to use long records of historic glacier fluctuations for comparison with model experiments, a dynamic ice flow model is needed. It calculates the response of glacier geometry to changes in specific mass balance. Cumulative glacier mass changes lead to changes in ice thickness which then influence the dynamic redistribution of mass by glacier flow (Haeberli 1995). In the following, a brief description of the ice flow model used in this study (Oerlemans 1997) is presented.

The prognostic equation of the ice flow model is a continuity equation describing conservation of ice volume:

$$\frac{\partial S}{\partial t} = -\frac{\partial (US)}{\partial x} + \omega B$$

Here, x is the coordinate along the flowline of the glacier, U is the vertical mean ice velocity, S is the area of a cross-section through the glacier perpendicular to the flowline (parameterized by a trapezoidal cross-section), B is the mass balance, and ω is the glacier width at the surface.

Both simple shearing flow and sliding are considered in the model. The vertical mean ice velocity U is determined by the local "driving stress" τ which is proportional to ice thickness H and surface slope $\partial h/\partial x$ (h is surface elevation). After rearrangement of equations (Oerlemans 1997) it follows that ice thickness H is governed by a non-linear diffusion equation which has to be solved by the ice flow model:

$$\frac{\partial H}{\partial t} = \frac{-1}{\omega_0 + \lambda H} \frac{\partial}{\partial x}\left[D \frac{\partial (b+H)}{\partial x} \right] + B$$

Here, H is the ice thickness, b and ω_0 are the elevation and the width of the bed of the glacier respectively. λ is determined by $(\omega\text{-}\omega_0)/H$. The diffusivity D can be expressed as:

$$D = (\omega_0 + \frac{\lambda}{2} H)\left[f_d \gamma H^5 \left(\frac{\partial h}{\partial x} \right)^2 + f_s \gamma H^3 \left(\frac{\partial h}{\partial x} \right)^2 \right]$$

with h as surface elevation, f_d and f_s as generalized viscosities referring to deformation and sliding respectively, and γ determined by $(\rho g)^3$ with ice density ρ and acceleration due to gravity g.

The equations are solved using standard numerical methods for parabolic equations. Ice thickness, ice velocity, ice volume, and glacier length L are obtained.

If a climatic state is changed stepwise from a state with equilibrium glacier length L_1 to a state with equilibrium glacier length L_2, the *(e-folding) response time for glacier length* t_{rL} is defined as the time the glacier needs to reach glacier length $L_2 - (L_2\text{-}L_1)/e$. Using the above model, the response time of Nigardsbreen to a stepwise change in the annual mass balance ($\delta B = \pm 0.4$ m water equivalent; Oerlemans 1997) is 68 years, for Rhonegletscher it is 61 years.

4. Auto-regressive processes for the simulation of mass balance using GCMs

In order to be able to quantify natural variations in glacier length with high statistical significance, long records of mass balance are required to force the dynamic ice flow model. Due to the long response times of the investigated glaciers (60-70 years, see previous section) mass balance time series in the order of thousands of years would be most suitable. However, the output of current coupled GCMs is naturally limited owing to high computational costs. For example, the ECHAM4/OPYC coupled GCM control integration used in this study has been integrated for 300 years.

Owing to these limitations, in this study, we apply a method to generate multi-millennia records of mass balance from temporally limited GCM integrations using auto-regressive (AR) processes.

a. General method

An auto-regressive process X_t of the order p, i.e. an AR(p) process, is generally defined as

$$X_t = \alpha_0 + \sum_{k=1}^{p} \alpha_k X_{t-k} + Z_t$$

where α_0, α_1, ..., α_p are constants (auto-regressive parameters), $\alpha_p \neq 0$, and Z_t is a white noise process. The name "auto-regressive" indicates that the process evolves by regressing past values towards the mean (with a "strength" determined by the auto-regressive parameters α_k) and then adding noise (von Storch and Zwiers 1999).

Our intention is now to fit an AR process of the above type to the mass balance time series simulated from GCM output and to generate a new mass balance time series of the desired length with similar properties. This is done using the following approach:

1. Calculation of the autocorrelation function of the original time series.
2. Fitting of an AR model to the time series, i.e. estimation of the auto-regressive parameters α_k (an iterative nonlinear least-squares procedure incorporating backforecasting is used; Box and Jenkins 1976).
3. Generation of a new time series with a similar autocorrelation function and standard deviation as the original.

This procedure is applied individually to the simulated mass balance records (Reichert et al. 2001) for Nigardsbreen and Rhonegletscher.

b. AR processes applied to Nigardsbreen and Rhonegletscher

The spectra of glacier mass balance as simulated by the GCM experiments (Reichert et al. 2001) are shown in Figure 3. Thin solid lines denote the spectra of equivalent red noise processes and dashed lines represent the 95% confidence levels for accepting the red noise null hypothesis. We generate 10000-year records of mass balance for the two glaciers with comparable frequency contents and similar standard deviations as the original time series.

We find that the mass balance time series for Nigardsbreen simulated by the coupled GCM experiment can be well approximated by a third order AR process (lag-1, lag-2, and lag-3 autocorrelation coefficients are 0.11, Table 1). Neither simply white noise nor red noise would be appropriate for the representation of the low frequency content of the mass balance characteristics. In fact, using a third order AR-process instead of a simple white noise process increases the variability in glacier length fluctuations by 36% as will be demonstrated in section 5. For Rhonegletscher, this impact is smaller, the simulated spectrum of mass balance may be approximated by a first order AR process (lag-1 coefficient: 0.04, lag-2 and lag-3 coefficients: < 0.01). We can expect a small impact on low frequency glacier length fluctuations as will be seen section 5.

Table 1 shows the auto-regressive parameters α_1, α_2, and α_3 as estimated by the AR model using the iterative nonlinear least-squares procedure. A higher than 3rd order AR process is not required, we find that it does not significantly improve the fit of the model any further. The differences between the autocorrelation coefficients of the original and the generated mass balance records (Table1; shown in brackets) are small and not significant for the purpose of the present study.

5. Simulation of glacier length fluctuations

The dynamic ice flow model for Nigardsbreen and Rhonegletscher is applied to the 10000-year mass balance records using AR processes obtained from the coupled GCM. Again, it should be emphasized that the simulated glacier length records are exclusively due to internal variations in the climate and glacier system since external forcing has been excluded in the GCM integration. We have simulated three individual 10000-year glacier length records for each glacier in order to investigate

a) the impact of using the AR-process determined by GCM output instead of simply using white noise, and
b) the influence of using the statistically downscaled GCM integrations instead of simply interpolating coarse GCM grid point output to the location of the glaciers.

The results are presented in Figure 4. Note that the time axes of the simulated records are not related to actual calendar years, we are solely interested in the possible range of internal glacier fluctuations. To facilitate the comparison with observations in the following section, the glacier model has been initialized to simulate variations around a mean level of observed preindustrial glacier lengths. The first glacier length record in each experiment [marked as “White Noise (Not Downscaled)” in the left part of each graph in Figure 4] is simulated simply by using gaussian white noise as mass balance forcing, with a standard deviation obtained from directly interpolated GCM grid point output without statistical downscaling. This means that the record represents glacier fluctuations that could be expected if neither the spectral content of GCM output nor downscaling played any role. The second record in each experiment [marked as “AR-Process (Not Downscaled)”] shows the impact of using a third order AR-process accounting for the spectral content of the GCM integrations. The standard deviations of the mass balance forcing records are similar to the first record, statistical downscaling is not applied. The third record [“AR-Process (Downscaled)”] additionally considers the impact of statistical downscaling and is therefore considered as the most comprehensive representation of glacier fluctuations simulated in this study.

The standard deviations σ of glacier length fluctuations for each experiment are shown below each record. For Nigardsbreen, using a third order AR-process determined from the coupled GCM experiment instead of a white noise process (Figure 4a) increases the variability in glacier fluctuations by 36% (standard deviations increase from 0.36 km to 0.49 km). As mentioned above, this emphasizes the high impact of the AR-process for the generation of low-frequency glacier fluctuations. Statistical downscaling additionally increases the variability by another 12% (from 0.49 km to 0.55 km).

As could be expected from the almost white mass balance spectra of Rhonegletscher (Figure 3b), the influence of the AR-process on glacier length variations for this glacier is only marginal (Figure 4b). However, due to the local setting of this glacier, the impact of downscaling is high, glacier length variability is increased by about 50% (from 0.19 km to 0.29 km; Figure 4b). This shows the substantial influence of statistical downscaling in this region of the Alps (Reichert et al. 2001). With respect to local observational data, the direct coarse grid point output of a GCM would have considerably underestimated the local climatic variability responsible for the length fluctuations of this glacier.

6. Comparison with observed glacier length fluctuations and statistical analysis

Simulated glacier fluctuations are compared to observed historical glacier length records for Nigardsbreen and Rhonegletscher. This allows to investigate whether preindustrial glacier fluctuations on one hand and the present-day retreat of the glaciers on the other hand can be explained by internal variations in the climate system as simulated by the GCM.

a. Historical records of glacier length changes

Observed or reconstructed glacier length variations for the two glaciers are shown in Figure 5. Various historic documents, terminal moraines, photogrammetric methods, and distance measurements have been combined to obtain this record (Hoelzle and Haeberli 1999).

During the first half of the 18^{th} century, Nigardsbreen advanced rapidly (the time of the beginning of the advance is uncertain) and reached a neoglacial maximum in 1748. Since then, a steady retreat has been observed until about 1990 which thereafter came to an end. The retreat of the glacier until 1900 (in the following noted as “Little Ice Age to 1900 retreat”) and can be found to be about 2 km for Nigardsbreen. The retreat until 1990 (“Little Ice Age to present-day retreat”) is roughly 4 km.

Rhonegletscher advanced at the beginning of the records until 1602, followed by a period for which glacier length remained within a range of 11.6-12.1 km until 1860. This time then marks the beginning of a rapid retreat. The “Little Ice Age to 1900 retreat” of the glacier, considering its maximum in 1602, is roughly 1.5 km, the “Little Ice Age to present-day retreat” is about 2.3 km.

b. Analysis of simulated glacier fluctuations

Figure 6 shows the first 2000 years of the simulated 10000-year glacier length records using AR-processes including downscaling, along with the observations for Nigardsbreen (Figure 6a) and Rhonegletscher (Figure 6b). As for figure 4, the time axes of the simulated records are not related to actual calendar years, we are solely interested in the possible range of internal glacier fluctuations. The simulated records show substantial changes in glacier length lasting for decades or even several centuries. Nevertheless, it appears that the observed retreat of the glaciers since their Little Ice Age maximum exceeds the amplitude of any glacier fluctuation in the corresponding simulated records using the coupled GCM. Fluctuations in the order of reconstructed variations before 1900 do however occur in the simulated records and may therefore be explainable by internal climate variations as simulated by the GCM.

For a further analysis, recurrence relationships for specific glacier length fluctuations are calculated. Figure 7 shows the distribution of glacier fluctuations for the complete 10000-year records. Glacier length changes are calculated as the difference between a local extreme value and the following extreme value, and the number of such “events” is plotted for a bin width of 0.2 km. The distribution is essentially symmetric with respect to negative and positive glacier length changes, retreat and advance are equally frequent. The maximum change in glacier length over the complete simulated 10000-year records is an advance of 2.8 km for Nigardsbreen (Figure 7a) lasting for about 200 years (Figure 6a; at around model year +1200). For Rhonegletscher, the maximum change is a retreat of 1.3 km (Figure 7b) lasting for more than 100 years (see Figure 6b; at around model year +1900). Figure 8 shows the corresponding recurrence relationships, the cumulative number of events N is plotted against glacier length changes ΔL, regardless of whether the glacier retreats or advances. The relationships can be well approximated by exponential regression, the recurrence relationships can be expressed as

$$\log N = -1.95\ \Delta L + 5.67 \qquad \text{(Nigardsbreen) and}$$

$$\log N = -3.48\ \Delta L + 5.78 \qquad \text{(Rhonegletscher).}$$

Note that the largest simulated glacier length fluctuations ($\Delta L > 2.5$ km for Nigardsbreen and $\Delta L > 1.1$ km for Rhonegletscher; Figure 8) are not completely in line with the regression. This can be expected since they occur only a few times within the 10000-year records thus representing a sampling problem.

c. Return periods of specific glacier length changes

On the basis of the above established recurrence relationships, we determine return periods α for the occurrence of specific glacier fluctuations due to internal climate variations as simulated using the coupled GCM integrations:

$$\alpha(\Delta L) = \frac{T_{sim}}{N(\Delta L)} = \frac{T_{sim}}{e^{b \cdot \Delta L + a}} = (T_{sim}\ e^{-a}) \cdot e^{-b \cdot \Delta L}$$

Here, T_{sim} is the time period simulated (10000 years in our experiments), *a* and *b* are the glacier specific regression parameters in the recurrence relationships (Nigardsbreen: $a = 5.67$, $b = -1.95$; Rhonegletscher: $a = 5.78$, $b = -3.48$; see above).

Table 2 shows that glacier fluctuations of at least 1 km can roughly be expected to occur every 250 years for Nigardsbreen and every 1000 years for Rhonegletscher. The observed "Little Ice Age to 1900 retreat" of 2 km for Nigardsbreen can be expected with a return period of about 1700 years exclusively due to internal climate fluctuations. For extreme glacier length fluctuations of 3 km we find return period of about 12000 years. For Rhonegletscher, the "Little Ice Age to 1900" retreat of 1.5 km is expected to occur every 5700 years. An extreme change of 2 km length has not been simulated for this glacier in the 10000-year record. However, in a longer integration we could expect it to occur with a return period of about 33000 years. Figure 9 is a graphical illustration of return periods.

d. Probabilities for the simulation of observed preindustrial glacier length changes and the present-day glacier retreat

Probabilities for specific glacier fluctuations within a given time interval can be calculated assuming that their occurrence generally follows a Poisson-process (events occur independently at random instants of time and at a constant mean rate per time interval; Priestley 1981). This approach also accounts for the fact that extreme glacier length changes that may not have been simulated in the 10000-year record still have a certain (although small) statistical probability of occurrence and may well occur in an even longer simulated record. The probability P for the occurrence of a glacier length change ΔL (represented by its return period α) within a time interval T can be expressed as

$$P(T,\alpha) = 1 - e^{-T/\alpha}$$

Substituting return period α with the definition in section 6.c, we may write

$$P(T,\Delta L) = 1 - \exp\left(-\frac{T}{T_{sim}} \cdot e^{b \cdot \Delta L + a}\right)$$

T_{sim} is the length of simulated records, a and b are the regression parameters obtained from the recurrence relationships.

The P (T, ΔL) relations for both Nigardsbreen and Rhonegletscher are illustrated in Figure 10. We show probabilities of occurrence P for glacier fluctuations ΔL within investigated time periods of $T = 100$, $T = 500$, $T = 2000$, and $T = 10000$ years.

For Nigardsbreen (Figure 10a), the probability that observed preindustrial glacier length changes of 2 km ("Little Ice Age to 1900 retreat", see Figure 5) occur within a time period of 10000 years exclusively due to internal climate variations is 99.7% (Figure 10a, solid line), these glacier fluctuations actually frequently occur in the simulated record (see Figure 7). On the other hand, the observed "Little Ice Age to present-day retreat" of 4 km (see Figure 5) has not been simulated due to internal climatic variability, the probability of occurrence is correspondingly small (11.1%). Looking at a time period of 2000 years only (Figure 10a, shaded line), the probability of occurrence for preindustrial glacier fluctuations is still 69%, whereas the probability for the present-day retreat drops to 2.3%.

For Rhonegletscher (Figure 10b), the probability of preindustrial glacier length changes within a 10000 year interval (solid line) is 80.4%, for the present-day retreat it is 9.9%. This means that the situation here is generally comparable to Nigardsbreen, preindustrial fluctuations are likely to occur in the simulated records whereas the present-day retreat is not simulated by any internal variation as represented by the coupled GCM.

7. Summary and Conclusions

In this study, we have applied a process-based modeling approach for the simulation of glacier fluctuations exclusively due to internal variations in the climate system using a downscaled coupled GCM experiment with ECHAM4/OPYC. A mass balance model of intermediate complexity and a dynamic ice flow model have been used to simulate glacier fluctuations for Nigardsbreen (Norway) and Rhonegletscher (Swiss Alps). We have shown that local downscaling has a considerable impact on glacier fluctuations, the variability in glacier length is substantially increased compared to simply using direct coarse GCM grid point output. Simulated glacier fluctuations have been statistically analyzed in order to compare them to observed or reconstructed historical glacier length records. On the basis of recurrence relationships, return periods of specific glacier fluctuation events have been determined. The observed retreat of Nigardsbreen since its

"Little Ice Age maximum" until 1900, can be expected to occur roughly every 1700 years exclusively due to internal climate fluctuations as simulated by the coupled GCM experiment. For Rhonegletscher, such a retreat can be expected with a return period of about 5700 years due to internal variability. Calculations of probabilities consequently indicate that for both glaciers, fluctuations as observed or reconstructed before 1900 are simulated to occur in all likelihood due to internal climate variability. On the other hand, the observed present-day retreat of the glaciers has not been simulated in the experiments and is therefore very unlikely to be explainable by internal variations in the climate system.

In order to broaden the basis for our main conclusions we have additionally performed similar experiments using control integrations of both the ECHAM4 model coupled to a Mixed-Layer-Ocean (ECHAM4/MLO; Roeckner 1997) and the Hadley Centre coupled model (HadCM2; Johns et al. 1997), obtaining similar results as described above.

We conclude that fluctuations of glaciers as far as observed or reconstructed before 1900, including their advance during the "Little Ice Age", can be explained by internal variations in the climate system as simulated by a GCM. This does not mean that other climatic forcing factors, for example, volcanic activity or solar irradiation changes (which will be investigated in future experiments using externally forced GCM integrations over long time periods) may not partly contribute to observed glacier fluctuations. Nevertheless, this study shows that internal climate variations have a dominant impact when trying to interpret dynamic records from individual glaciers.

Another important point derives from the fact that the present-day glacier retreat exceeds the amplitude of any simulated glacier fluctuation using the GCM control integrations. We have shown that it is consequently unlikely that this retreat can be entirely caused by internal climate variability and that external forcing must be a contributing factor. In additional experiments, we have investigated the role of anthropogenic forcing as a potential candidate. The process-based approach developed in this study has been applied to transient integrations with ECHAM4/OPYC forced by increasing concentrations of greenhouse gases, sulphate aerosols, and tropospheric ozone over the period 1860-2050 (Roeckner et al. 1999). In spite of a considerable impact of internal variations superimposed on the general trend over this period, results for Nigardsbreen indicate that the observed present-day retreat is comparable to the simulated retreat expected due to anthropogenic forcing. The experiments therefore suggest that climate change due to anthropogenic forcing is a likely explanation for the observed glacier retreat.

This study is spatially limited to the investigated glacier sites and only future experiments using a large number of globally-distributed glaciers will allow to draw conclusions on a global scale. However, our results are in line with recent studies indicating that rates and acceleration trends of global glacier mass changes over at least the past four decades correspond to the overall effects of anthropogenic forcing (Haeberli et al. 1999; Dyurgerov and Meier 2000). The transient GCM experiments with ECHAM4/OPYC additionally predict a considerable future retreat of Nigardsbreen due to anthropogenic forcing. In fact, a retreat of about 20% of the present-day glacier length (10.3 km) is simulated by the model until 2050.

Acknowledgments. The authors would like to thank E. Roeckner, H. Graßl, D. Dommenget, J. Jones, and A. Tompkins, for their valuable scientific support. Prof. Hans von Storch is thanked for help concerning several statistical issues within this study. We thank N. Noreiks for help on graphic representation. Glacier mass balance and glacier length data were obtained from the World Glacier Monitoring Service (WGMS), the ECMWF provided meteorological reanalyses, and the Swedish Meteorological and Hydrological Institute (SMHI) contributed operational weather station data. The study was supported by the European Commission under contract ENV4-CT95-0072 and by NOAA/ESH grant NA86GP0437. The Alexander von Humboldt Foundation is thanked for supporting B. K. Reichert as a Feodor Lynen Fellow. Model simulations were performed at the German Climate Computing Center (DKRZ) in Hamburg.

References

Bengtsson, L., 2001: Uncertainties of global climate prediction, *Proc. of the Symposium on Global Biogeochemical Cycles in the Climate System, September 22-27, 1998*. Max-Planck-Inst. für Biogeochem., Jena, Germany, in press.

Bengtsson, L., and B. K. Reichert, 2000: Global climate change and natural climate variability - What are their reasons? (in German). *Energie und Umwelt - Wo liegen optimale Lösungen?* S. Wittig and J. Wolfrum, Eds., Union der deutschen Akademien der Wissenschaften und Heidelberger Akademie der Wissenschaften, Springer Verlag, 27-57.

Box, G. E. P., and G. M. Jenkins, 1976: *Time series analysis: forecasting and control*. Holden-Day.

Cubasch, U. R., R. Voss, G. C. Hegerl, J. Waszkewitz, and T. J. Crowley, 1997: Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model. *Clim. Dyn.,* **13**, 757-767.

Dyurgerov, M. B., and M. F. Meier, M. F., 2000: Twentieth century climate change: Evidence from small glaciers. *Proc. Natl. Acad. Sci. U. S. A.,* **97***,* 1406-1411.

Gibson, J. K., P. Kållberg, S. Uppala, A. Nomura, A. Hernandez, and E. Serrano, 1997: ERA Description, *ECMWF Re-Anal. Proj. Rep. Ser.*, *Rep. 1*. Eur. Cent. for Medium-Range Weather Forecasts, Reading, England.

Grove, J. M., 1988: *The Little Ice Age*. Methuen.

Haeberli, W., 1995: Glacier fluctuations and climate change detection. *Geogr. Fis. Dinam. Quat.,* **18***,* 191-199.

Haeberli, W., R. Frauenfelder, M. Hoelzle, and M. Maisch, 1999: On rates and acceleration trends of global glacier mass changes. *Geografiska Annaler*, **81**, 585-591.

Hansen, J., I. Fung, R. Ruedy, and M. Sato, 1992: Potential climate impact of Mount Pinatubo eruption. *Geophys. Res. Lett.,* **19**, 215-218.

Hasselmann, K., 1976: Stochastic Climate Models I: Theory. *Tellus,* **28**, 473-485.

Hoelzle, M., and W. Haeberli, 1999: World glacier monitoring service, world glacier inventory. Digital data available from the *National Snow and Ice Data Center*, nsidc@kryos.colorado.edu, Univ. of Colorado, Boulder, Colorado.

Hoyt, D. V., and K. H. Schatten, 1993: A discussion of plausible solar irradiance variations 1700-1992. *J. Geophys. Res.,* **98**, 18895-18906.

Intergovernmental Panel on Climate Change (IPCC), 1990: *Climate Change, The IPCC Scientific Assessment*. J. T. Houghton and Coauthors, Eds., Cambridge Univ. Press.

Johns, T. C., R. E. Carnell, J. F. Crossley, J. M. Gregory, J. F. B. Mitchell, C. A. Senior, S. F. B. Tett, and R. A. Wood, 1997: The Second Hadley Centre coupled ocean-atmosphere GCM: Model description, spinup and validation. *Clim. Dynam*., **13**, 103-134.

Lean, J., J. Beer, and R. S. Bradley, 1995: Reconstruction of solar irradiance since 1610: Implications for climate change. *Geophys. Res. Letters,* **22**, 3195-3198.

Lindzen, R. S., and C. Giannitsis, 1998: On the climatic implications of volcanic cooling. *J. Geophys. Res.,* **103**, 5929-5941.

Mikolajewicz, U. and E. Maier-Reimer, 1990: Internal secular variability in an ocean general circulation model. *Clim. Dyn.,* **4**, 145-156.

Oberhuber, J. M., 1993: Simulation of the Atlantic circulation with a coupled sea ice - mixed layer - isopycnal general circulation model. Part I: Model description. *J. Phys. Oceanogr.,* **22**, 808-829.

Oerlemans, J., 1992: Climate sensitivity of glaciers in southern Norway: application of an energy-balance model to Nigardsbreen, Helstugubreen and Alfotbreen. *J. Glaciol.,* **38***,* 223-232.

Oerlemans, J., 1997: A flow-line model for Nigardsbreen: Projection of future glacier length based on dynamic calibration with the historic record. *Ann. Glaciol.,* **24**, 382-389.

Oerlemans, J., 2000: Holocene glacier fluctuations: is the current rate of retreat exceptional? *Ann. Glaciol.*, **31**, 39-44.

Oerlemans, J., 2001: *Glaciers and Climate Change*. Balkema Publishers.

Oerlemans, J., and B. K. Reichert, 2000: Relating glacier mass balance to meteorological data using a seasonal sensitivity characteristic (SSC). *J. Glaciol.,* **46**, 1-6.

Paterson, W. S. B., 1994: *The Physics of Glaciers*. 3rd ed., Pergamon.

Priestley, M. B., 1981: *Spectral Analysis and Time Series*. Academic Press.

Reichert, B. K., L. Bengtsson, and O. Åkesson, 1999: A statistical modeling approach for the simulation of local paleoclimatic proxy records using general circulation model output. *J. Geophys. Res.,* **104**, 19071-19083.

Reichert, B. K., L. Bengtsson, and J. Oerlemans, 2001: Midlatitude forcing mechanisms for glacier mass balance investigated using general circulation models. *J. Climate*, **14***,* 3767-3784.

Roeckner, E., L. Arpe, L. Bengtsson, M. Christoph, M. Claussen, L. Dümenil, M. Esch, M. Giorgetta, U. Schlese, and U. Schulzweida, 1996: The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. *Rep. 218*, Max-Planck-Inst. für Meteorol., Hamburg, Germany.

Roeckner, E., 1997: Climate sensitivity experiments with the MPI/ECHAM4 model coupled to a slab ocean (abstract), in *Euroclivar Workshop on Cloud Feedbacks and Climate Change*, edited by C. A. Senior and J. F. B. Mitchell, pp. 20, Hadley Cent. for Clim. Predict. and Res., Bracknell, England.

Roeckner, E., L. Bengtsson, J. Feichter, J. Lelieveld and H. Rodhe, 1999: Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle. *J. Climate,* **12**, 3004-3032.

Sarachik, E. S., M. Winton, and F. L. Yin, 1996: Mechanisms for decadal-to-centennial climate variability, in *Decadal climate variability*, eds. D. L. T. Anderson and J. Willebrand, *NATO ASI series, vol. 44*, Springer.

von Storch, H., and F. W. Zwiers, 1999: *Statistical Analysis in Climate Research*. Cambridge Univ. Press.

Tables

Table 1. Autocorrelation coefficients of the original GCM and of the generated 10000-year mass balance records (in brackets) using a third order AR process determined by the AR parameters α_1, α_2, and α_3 estimated by the AR model.

	Autocorrelation Coefficients		
	lag-1	lag-2	lag-3
Nigardsbreen	0.11 (0.12)	0.11 (0.12)	0.11 (0.11)
	α_1=0.091	α_2=0.089	α_3=0.092
Rhonegletscher	0.04 (0.04)	0.003 (0.002)	0.004 (0.003)
	α_1=0.044	α_2=-0.004	α_3=0.010

Table 2. Return Periods for Specific Glacier Length Fluctuations

Length Change	Nigardsbreen (years)	Rhonegletscher (years)
$\Delta L \geq 0.5$ km	92	176
$\Delta L \geq 1.0$ km	243	1004
$\Delta L \geq 1.5$ km	644	5732
$\Delta L \geq 2.0$ km	1710	32732
$\Delta L \geq 2.5$ km	4537	($>10^5$)
$\Delta L \geq 3.0$ km	12039	($>10^6$)

Figure Captions

FIG. 1. Process-based modeling approach for the simulation of glacier fluctuations applied in this study. Statistically downscaled GCM integrations are used for mass balance calculations using glacier-specific seasonal sensitivity characteristics (SSCs) based on a mass balance model. Glacier length records are simulated using a dynamic ice flow model and can finally be compared to observed or reconstructed historical glacier fluctuations.

FIG. 2. Glacier-specific Seasonal Sensitivity Characteristic (SSC) for (a) Nigardsbreen and (b) Rhonegletscher (Reichert et al. 2001). The SSC represents the dependence of glacier mass balance on monthly perturbations in temperature (solid bars; in meter water equivalent (mwe)/K) and precipitation (shaded bars; in (mwe)/(10%)).

FIG. 3. Spectra of glacier mass balance records for (a) Nigardsbreen and (b) Rhonegletscher as simulated by the coupled GCM experiment. Thin solid lines denote the spectra of equivalent red noise processes and dashed lines represent the 95% confidence levels for accepting the red noise null hypothesis.

FIG. 4. 10000-year records of simulated glacier length fluctuations for (a) Nigardsbreen and (b) Rhonegletscher. The figure demonstrates the impact of using AR-processes determined by GCM output as mass balance forcing (record in the middle) instead of simply using white noise with the same variance (left records), and the impact of statistical downscaling (right records). Standard deviations σ of glacier length are shown below each record.

FIG. 5. Observed or reconstructed historical glacier length variations for Nigardsbreen (solid line; diamonds are data points) and Rhonegletscher (dotted line; circles are data points). Data from Hoelzle and Haeberli (1999).

FIG. 6. Observed and simulated glacier fluctuations for (a) Nigardsbreen and (b) Rhonegletscher. Simulated glacier length fluctuations are exclusively due to internal variations in the climate system using AR-processes from the downscaled control integration of the ECHAM4/OPYC coupled GCM.

FIG. 7. Histogram of simulated glacier fluctuations using the downscaled coupled GCM integration. The number of events represents specific glacier length changes in the simulated 10000-year records and is plotted for a bin width of 0.2 km. Negative (positive) values indicate glacier retreat (advance).

FIG. 8. Recurrence relationships showing the cumulative number of glacier fluctuation events N for a minimum glacier length change ΔL. The relationships are well approximated by exponential regression.

FIG. 9. Graphical illustration of return period α in years for glacier length changes larger than ΔL (in km) for Nigardsbreen (solid line) and Rhonegletscher (shaded line).

FIG. 10. Probabilities P for the occurrence of simulated glacier length changes ΔL within a time period of investigation T, exclusively due to internal climate variations as simulated using the ECHAM4/OPYC coupled GCM. For (a) Nigardsbreen, the probability that observed preindustrial glacier length changes of 2 km ("Little Ice Age to 1900 retreat") occur within a time period of 10000 years is 99.7%, whereas the present-day retreat (4 km) is unlikely to be explained by internal variability ($P = 11.1\%$). For (b) Rhonegletscher, the probabilities are 80.4% and 9.9% respectively.

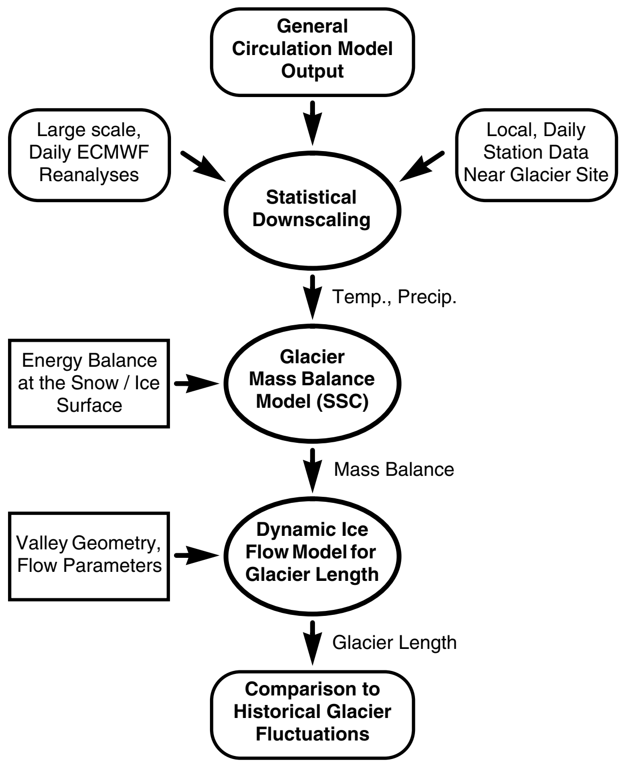

General Circulation Model Output
Large scale, Daily ECMWF Reanalyses
Local, Daily Station Data Near Glacier Site
Statistical Downscaling
Temp., Precip.
Energy Balance at the Snow / Ice Surface
Glacier Mass Balance Model (SSC)
Mass Balance
Valley Geometry, Flow Parameters
Dynamic Ice Flow Model for Glacier Length
Glacier Length
Comparison to Historical Glacier Fluctuations

Figure 1.

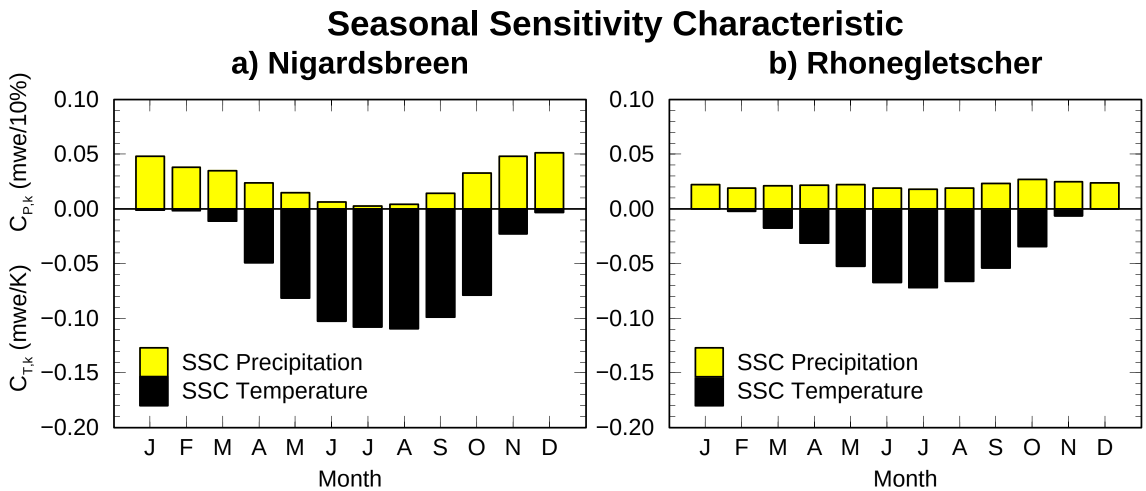

Seasonal Sensitivity Characteristic
a) Nigardsbreen
b) Rhonegletscher
C_P,k (mwe/10%)
C_T,k (mwe/K)
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
SSC Precipitation
SSC Temperature
J F M A M J J A S O N D
Month

Figure 2.

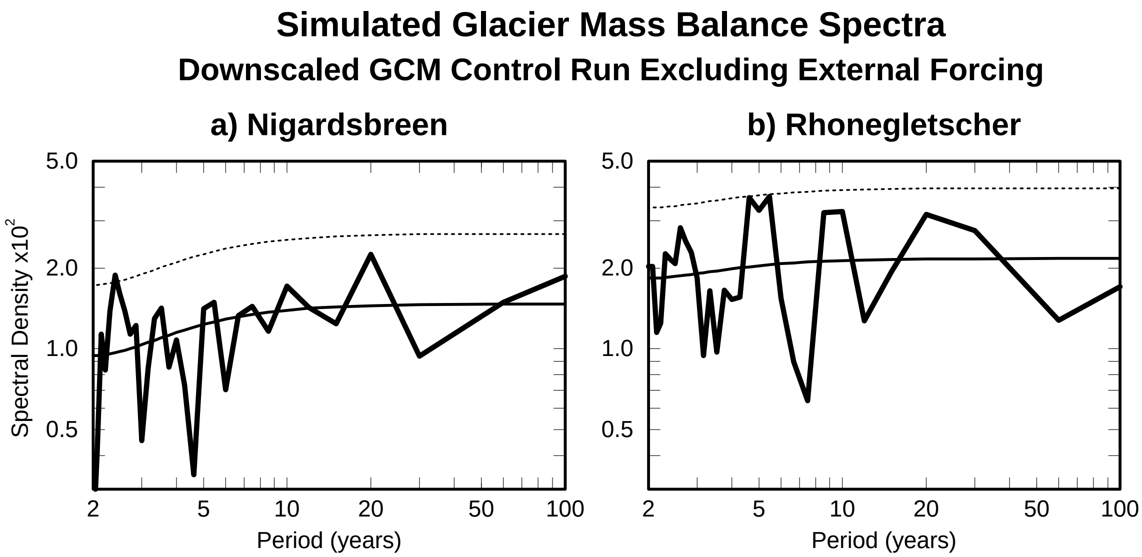

Simulated Glacier Mass Balance Spectra
Downscaled GCM Control Run Excluding External Forcing
a) Nigardsbreen
b) Rhonegletscher
Spectral Density x10^2
5.0
2.0
1.0
0.5
2
5
10
20
50
100
Period (years)

Figure 3.

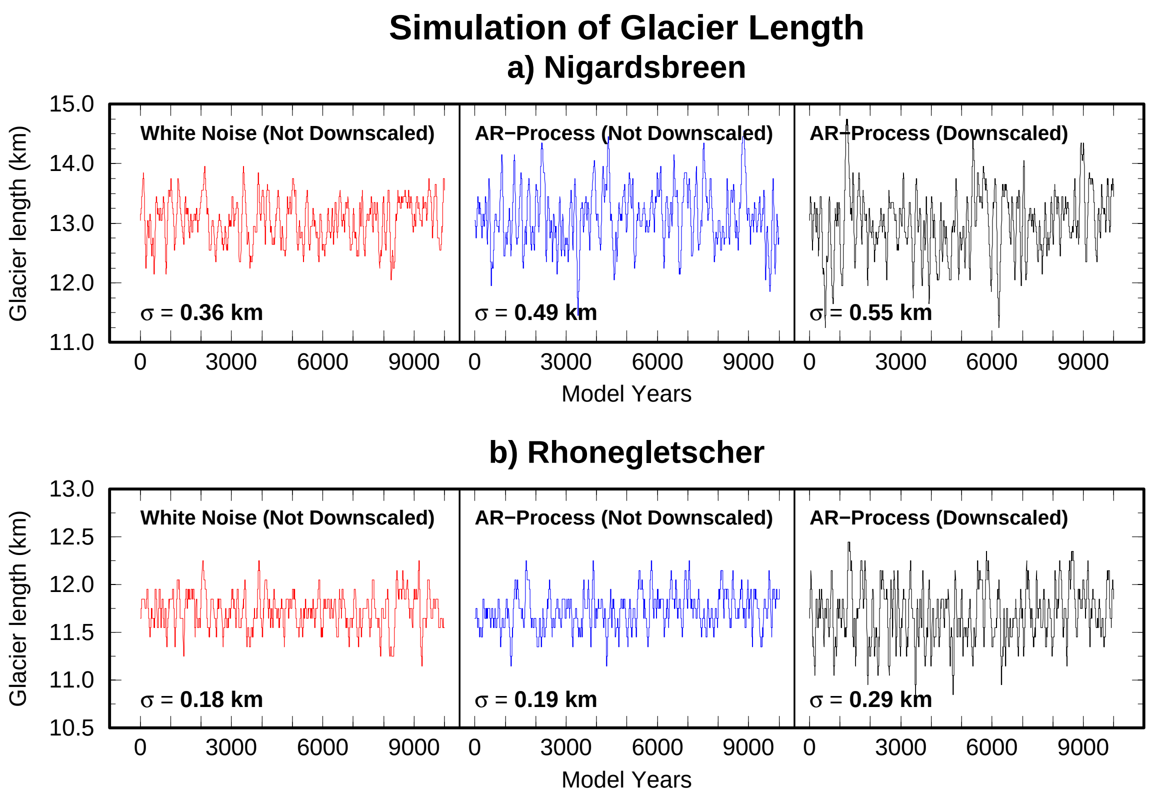

Simulation of Glacier Length
a) Nigardsbreen
Glacier length (km)
15.0
14.0
13.0
12.0
11.0
White Noise (Not Downscaled)
AR−Process (Not Downscaled)
AR−Process (Downscaled)
σ = 0.36 km
σ = 0.49 km
σ = 0.55 km
0
3000
6000
9000
Model Years
b) Rhonegletscher
Glacier length (km)
13.0
12.5
12.0
11.5
11.0
10.5
White Noise (Not Downscaled)
AR−Process (Not Downscaled)
AR−Process (Downscaled)
σ = 0.18 km
σ = 0.19 km
σ = 0.29 km
0
3000
6000
9000
Model Years

Figure 4.

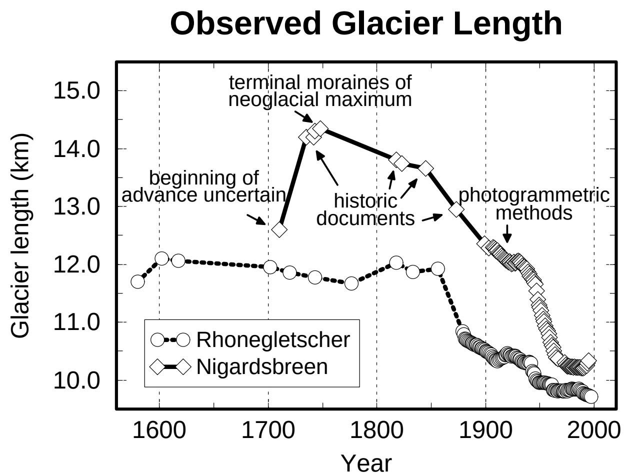

Observed Glacier Length
terminal moraines of
neoglacial maximum
beginning of
advance uncertain
historic
documents
photogrammetric
methods
Rhonegletscher
Nigardsbreen
Glacier length (km)
15.0
14.0
13.0
12.0
11.0
10.0
1600
1700
1800
1900
2000
Year

Figure 5.

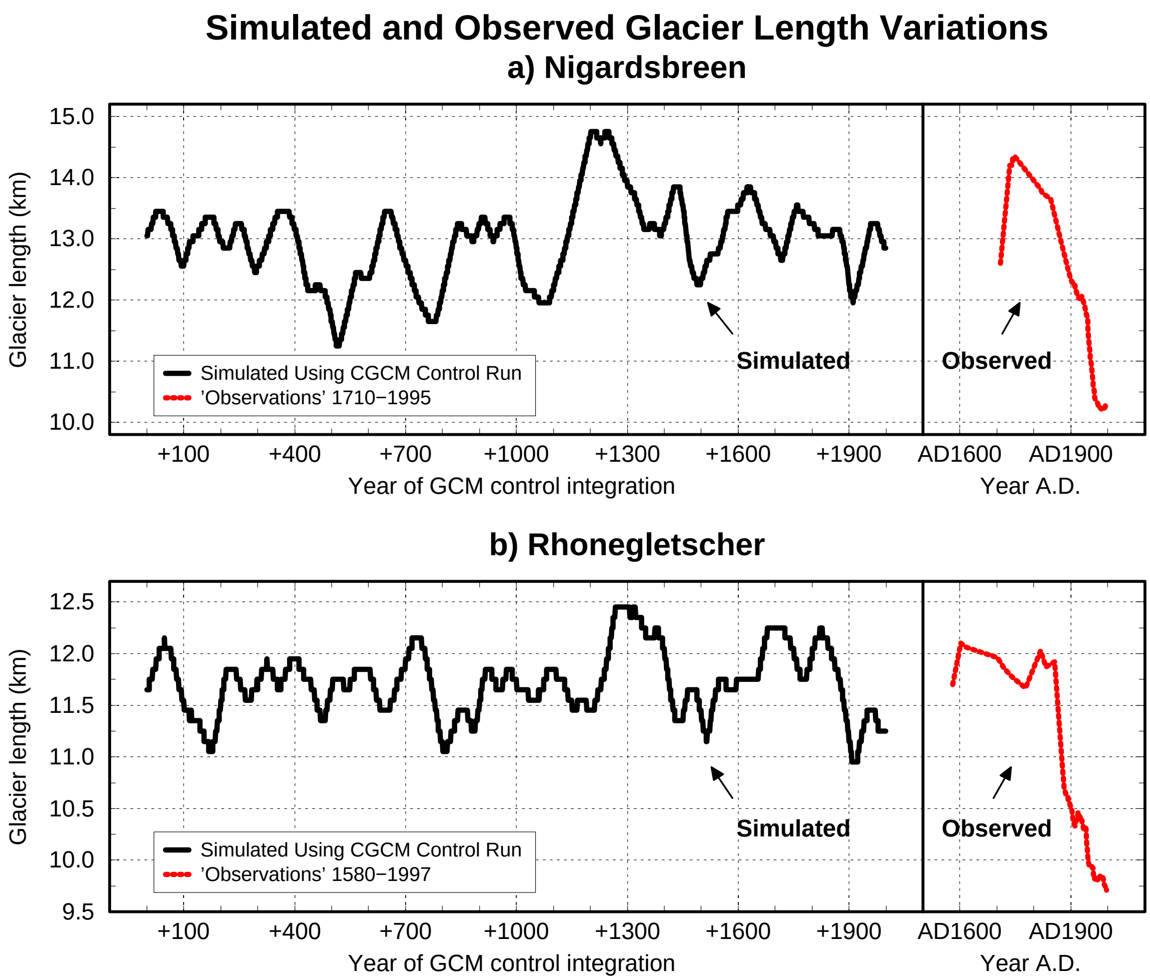

Simulated and Observed Glacier Length Variations
a) Nigardsbreen
Glacier length (km)
15.0
14.0
13.0
12.0
11.0
10.0
Simulated
Observed
Simulated Using CGCM Control Run
'Observations' 1710−1995
+100
+400
+700
+1000
+1300
+1600
+1900
AD1600
AD1900
Year of GCM control integration
Year A.D.
b) Rhonegletscher
Glacier length (km)
12.5
12.0
11.5
11.0
10.5
10.0
9.5
Simulated
Observed
Simulated Using CGCM Control Run
'Observations' 1580−1997
+100
+400
+700
+1000
+1300
+1600
+1900
AD1600
AD1900
Year of GCM control integration
Year A.D.

Figure 6.

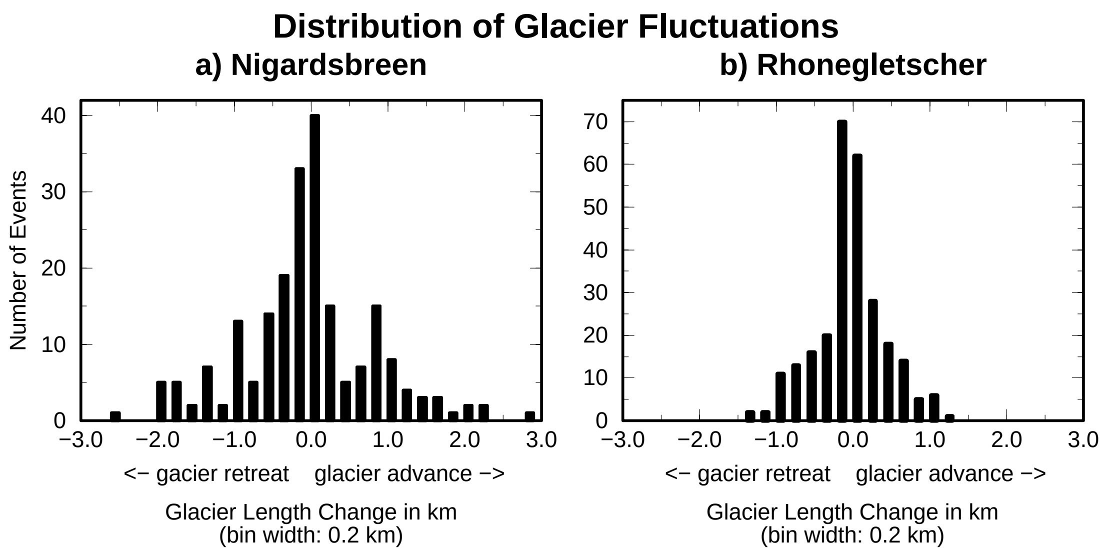

Distribution of Glacier Fluctuations
a) Nigardsbreen
b) Rhonegletscher
Number of Events
0
10
20
30
40
50
60
70
−3.0
−2.0
−1.0
0.0
1.0
2.0
3.0
<− gacier retreat
glacier advance −>
Glacier Length Change in km
(bin width: 0.2 km)

Figure 7.

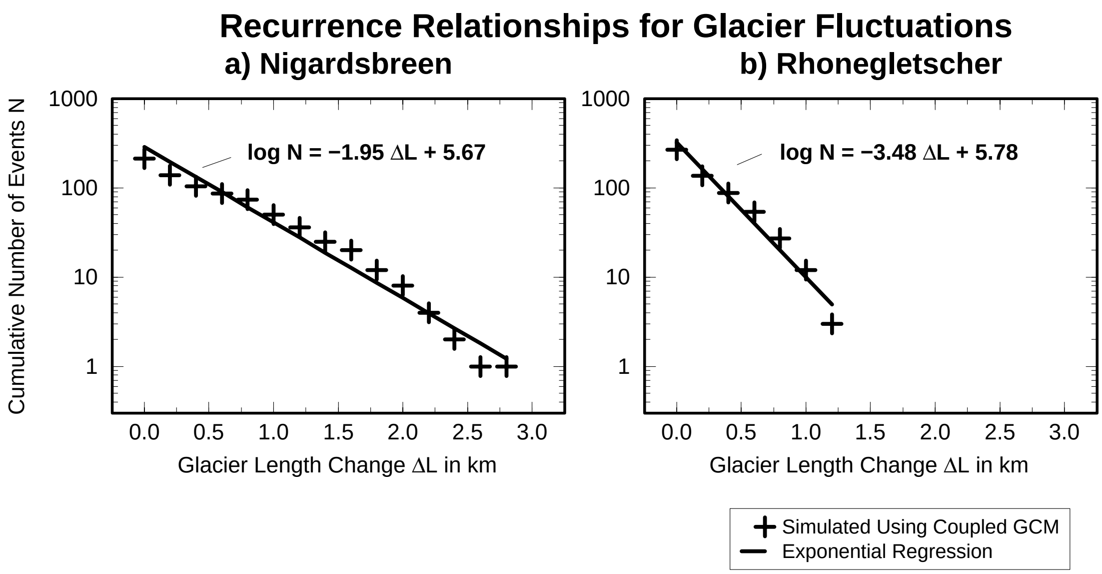

Recurrence Relationships for Glacier Fluctuations
a) Nigardsbreen
b) Rhonegletscher
Cumulative Number of Events N
1000
100
10
1
log N = −1.95 ΔL + 5.67
log N = −3.48 ΔL + 5.78
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Glacier Length Change ΔL in km
Simulated Using Coupled GCM
Exponential Regression

Figure 8.

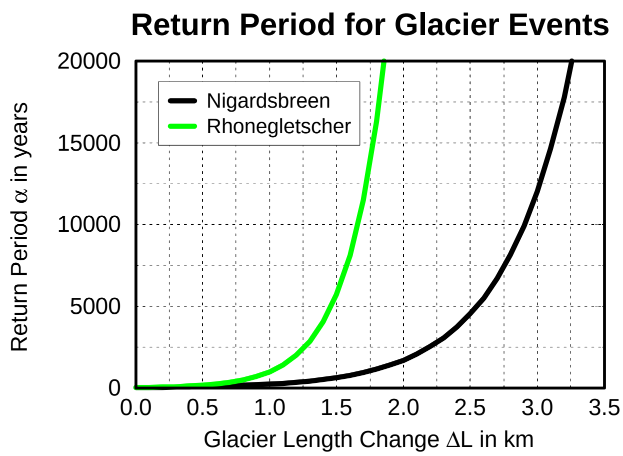
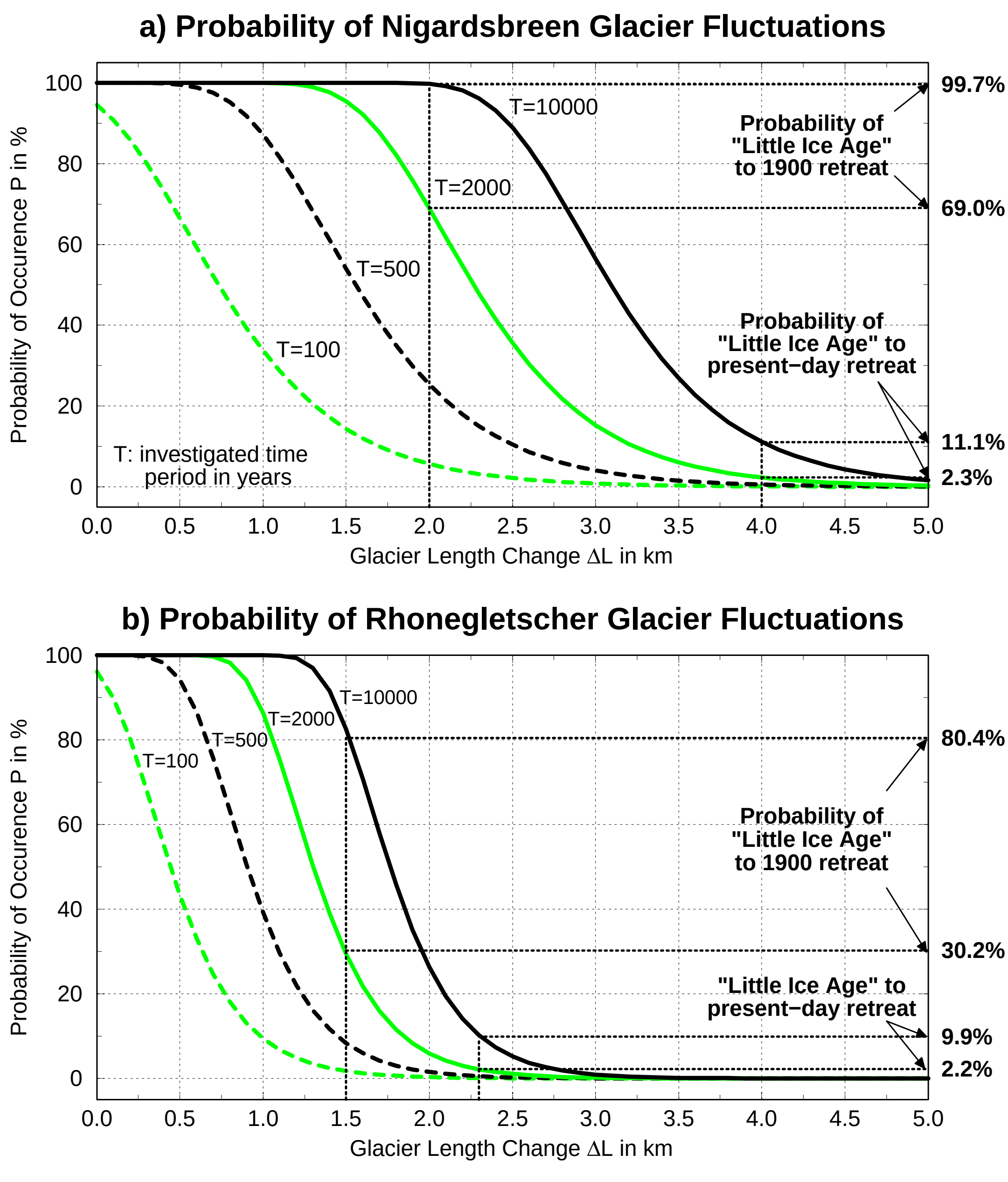

Return Period for Glacier Events
Nigardsbreen
Rhonegletscher
Return Period α in years
20000
15000
10000
5000
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Glacier Length Change ΔL in km

Figure 9.



a) Probability of Nigardsbreen Glacier Fluctuations
Probability of Occurence P in %
Glacier Length Change ΔL in km
T=10000
T=2000
T=500
T=100
T: investigated time period in years
Probability of "Little Ice Age" to 1900 retreat
99.7%
69.0%
Probability of "Little Ice Age" to present−day retreat
11.1%
2.3%
b) Probability of Rhonegletscher Glacier Fluctuations
Probability of Occurence P in %
Glacier Length Change ΔL in km
T=10000
T=2000
T=500
T=100
Probability of "Little Ice Age" to 1900 retreat
80.4%
30.2%
"Little Ice Age" to present−day retreat
9.9%
2.2%

Figure 10.

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ISSN 0937-1060