Clim Dyn
DOI 10.1007/s00382-013-1758-0

The absence of memory in the climatic forcing of glaciers

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Received: 23 October 2012 / Accepted: 27 March 2013

Abstract Glaciers respond to both long-term, persistent climate changes as well as the year-to-year variability that is inherent to a constant climate. Distinguishing between these two causes of length change is important for identifying the true climatic cause of past glacier fluctuations. A key step in addressing this is to determine the relative importance of year-to-year variability in climate relative to more persistent climate fluctuations. We address this question for European climate using several long-term observational records: a century-long, Europe-wide atmospheric gridded dataset; longer-term instrumental measurements of summertime temperature where available (up to 250 years); and seasonal and annual records of glacier mass balance (between 30 and 50 years). After linear detrending of the datasets, we find that throughout Europe persistence in both melt-season temperature and annual accumulation is generally indistinguishable from zero. The main exception is in Southern Europe where a degree of interannual persistence can be identified in summertime temperatures. On the basis of this analysis, we conclude that year-to-year variability dominates the natural climate forcing of glacier fluctuations on timescales up to a few centuries.

Keywords Glaciers · Climate persistence · Climate variability

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1 Introduction

In many locations, reconstructions of past glacier fluctuations constitute the primary records of past climates. A pervasive interpretation in the scientific literature is that such fluctuations reflect significant and persistent climate changes. However, several recent studies have demonstrated that for typical alpine glaciers, year-to-year variability alone can drive kilometer-scale, century-scale fluctuations in length (Oerlemans 2000, 2001; Reichert et al. 2002; Roe and O'Neal 2009; Huybers and Roe 2009; Roe 2011). Such a large response leads naturally to the question of how this year-to-year variability compares with other climatic forcings on glaciers.

In a world undergoing anthropogenic climate change a climate time series can be decomposed into the human-forced trend and the natural variability. We are interested in characterizing the natural variability, which can in turn be decomposed into two pieces: the essentially random year-to-year fluctuations that lack persistence from one year to the next (hereafter referred to as *interannual* variability); and a residual that is persistent (hereafter referred to as *persistent* variability) and that reflects either memory in the climate system or a sustained natural climate forcing such as volcanic aerosols or solar luminosity. Glaciers are dynamical systems driven by climate, and as such, will respond to all three components. In this study we remove the trend, and characterize the residual natural variability. In particular we focus on the relative importance of interannual variability versus persistent variability for driving glacier fluctuations.

An outline of this study is as follows. We first present a qualitative description of a glacier's response to climate variability. We then concentrate on the climate variables of most importance for driving midlatitude glacier length fluctuations, namely annual precipitation and melt-season temperature. We also focus on Europe, as it has an extensive amount of meteorological data as well as glacier mass balance records available. Specifically, we analyze: (1) a continent-wide, century-long, gridded atmospheric dataset; (2) a selection of individual station records of length up to 250 years; and (3) the shorter, but very relevant, direct records of glacier mass balance. The degree of persistence is evaluated by calculating a decorrelation time and also by fitting higher order autoregressive models to the data. The importance of the persistent component of the variability is evaluated using a linear glacier model. For all three datasets, the interannual component of variability dominates over the persistent component. Finally, we evaluate the spatial coherence of the natural climate variability in order to understand how independent the climate forcing is for different glaciers. Not surprisingly, we find climate variability is highly coherent on regional scales, meaning that over scales of hundreds of kilometers glaciers experience very similar interannual climate variability.

Our results are consistent with earlier studies that also concluded interannual climate variability constitutes a major driver of glacier fluctuations in Europe (Oerlemans 2000; Reichert et al. 2002). Because we restrict our analyses to instrumental records of climate, these results apply most directly to decadal- and centennial-scale glacier fluctuations. The relevance for longer-term fluctuations is broached in the discussion.

2 A spectral interpretation of a glacier's response to climate

The response of a dynamic system with memory to stochastic forcing is described in detail by many standard statistics textbooks (e.g., Jenkins and Watts 1968; von Storch and Zwiers 1999). In climate science, the concept was introduced by Hasselmann (1976), who suggested that persistence in sea-surface temperature reflects the integrated response of the ocean mixed layer to random weather variability. Drawing from these ideas, Oerlemans (2000, 2001) explored the effect of stochastic forcing on glaciers and calculated, for typical model parameters, a standard deviation (1σ) of 650 m in glacier length. Since such a glacier would spend approximately 5 % of its time outside of $\pm 2\sigma$, kilometer-scale fluctuations would be expected quite frequently. A general review of the relationship between dynamic response time, system feedbacks, and variability can be found in Roe (2009).

The potential for non-persistent climate variability to drive persistent long-term glacier fluctuations can be demonstrated by considering the spectra of the climate forcing and glacier response (illustrated schematically in Fig. 1). Consider a time series of a climate variable without persistence (Fig. 1a). The autocorrelation function of such a time series is a delta function, and equals one at zero-lag, and zero for all other lags. By definition, the power spectrum of the time series is the Fourier transform of this delta function, which is a constant. The spectrum thus has equal power at all frequencies (Fig. 1c), and by analogy with light it is said to be white. In other words, this time series that by construction has no persistence, nonetheless has equal power at all frequencies in its spectrum. There is no contradiction because the phases of individual frequencies in this spectrum are random, and so the individual components of the Fourier series cancel out on average, leaving no persistence in the resulting time series.

A common misinterpretation of climate spectra is to infer that spectral power at a given period equates to persistence on that timescale. But, as the preceding demonstrates, that is not necessarily true. Power at centennial timescales in a spectrum does not imply centennial persistence or predictability—it can be purely an artifact of the way power spectra are generated. The true measure of the persistence (and predictability) in a time series is its autocorrelation function—which reflects how long a time series retains information about previous states.

How does a glacier respond to such a climate power spectrum? No matter the details of a glacier's dynamics, its length variations will always act as some form of a low-pass filter: a glacier's inertia prevents it from responding to high frequency fluctuations, but the glacier can respond to lower frequencies. Thus, the spectrum of the glacier response will be as depicted in Fig. 1c—greater power at lower frequencies. Again, by analogy with light, it is said to have a red spectrum. Mathematically, when the time series of the glacier's response is reconstructed from the spectrum, even though the phases are still random, adjacent frequencies no longer cancel out in the region where the power is changing rapidly, and the time series of length variations will exhibit persistent fluctuations (Fig. 1b).

3 European climate

3.1 Spatial patterns of climate

We begin by reviewing the basic patterns of climate across Europe, focusing on two fields that are particularly relevant for glacier mass balance: melt-season temperature and annual precipitation. Melt-season temperature is defined here as the mean surface temperature between June and September. Annual precipitation is used as a rough approximation for accumulation. Obviously, other factors influencing glacier mass balance could be considered, such as a temperature-dependent rain/snow criterion, cloudiness, and relative

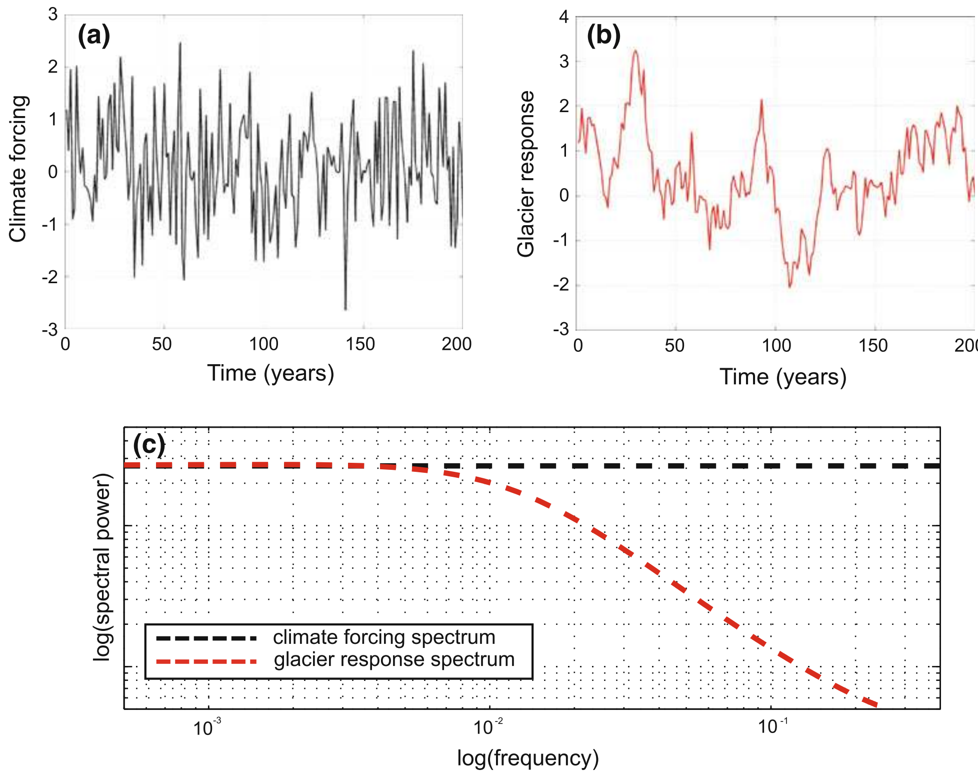

Fig. 1 **a** A random realization of a hypothetical climate variable equivalent to white noise; **b** A schematic time series of how a glacier might process the climate input of (**a**)—note the low frequencies prevalent in the response; **c** Illustrative power spectra of both the climate time series in (**a**) and the glacier response in (**b**). White noise has power at all frequencies, while the red spectrum of the glacier has considerably more power at low frequencies. Units on the *y* axis are arbitrary

humidity. Since our main purpose is to characterize the temporal persistence and spatial coherence of relevant climate fields, a simple treatment provides a conservative answer in the sense that a more complicated representation of ablation involving more climate fields each with their own attendant variability would likely have less persistence.

The first dataset we use is an observational gridded climate record for Europe made available by the Climatic Research Unit, and which has been comprehensively evaluated and quality controlled (Mitchell et al. 2004). Individual station data are averaged together for each grid cell with a spatial resolution of 10 min (i.e., 1/6°), covering the century from 1901 to 2000 (Mitchell et al. 2004). We note that, even at this high resolution, the dataset is not capable of capturing the orographic influences on climate at the scale individual glaciers experience. Moreover, the dataset interpolates from relatively sparse station data in mountainous terrain, and so the detailed spatial patterns must be regarded with caution. However, it is important to emphasize again that our main goal is to determine the persistence of the climate signal, and so this dataset provides a conservative answer (i.e., higher resolution data would be unlikely to exhibit greater persistence).

The climatology of this dataset is shown in Fig. 2a, b, in which the orographic, maritime, and latitudinal influences are evident. In the northern latitudes, the Scandinavian Mountains divide Scandinavia into two regions: a wet region on the windward side of the mountains that covers much of Norway, and a generally dry region in the leeward interior. Temperatures increase to the south, with the exception of the cooler, high-elevation Alps. The Alps also exert an influence over the local climate: orographic lifting of air on the flanks keeps adjacent areas cool and wet, and also contributes to the relative aridity of the continental interior. The variability of the dataset is shown in Fig. 2c, d. The standard deviation of melt-season temperature is quite homogenous, with values of 0.8–1.0 °C over much of Europe. On the other hand, the standard deviation of precipitation has a pattern that closely resembles the climatology: the largest values are in the wet, mountainous regions and along the coast.

3.2 Persistence of climate variability

To characterize the persistence in these climate time series, we first calculate a simple decorrelation timescale from a first-order autoregressive model. We then fit the data with higher-order autoregressive models to determine if additional complicated patterns of autocorrelation are present.

3.2.1 A simple model of persistence

A straightforward way to characterize persistence in a general time series, $x(t)$, is with an autocorrelation analysis (e.g., vonStorch and Zwiers 1999). The simplest representation of this is:

$$x_t = a_1 x_{t-\Delta t} + a_0 u_t \qquad (1)$$

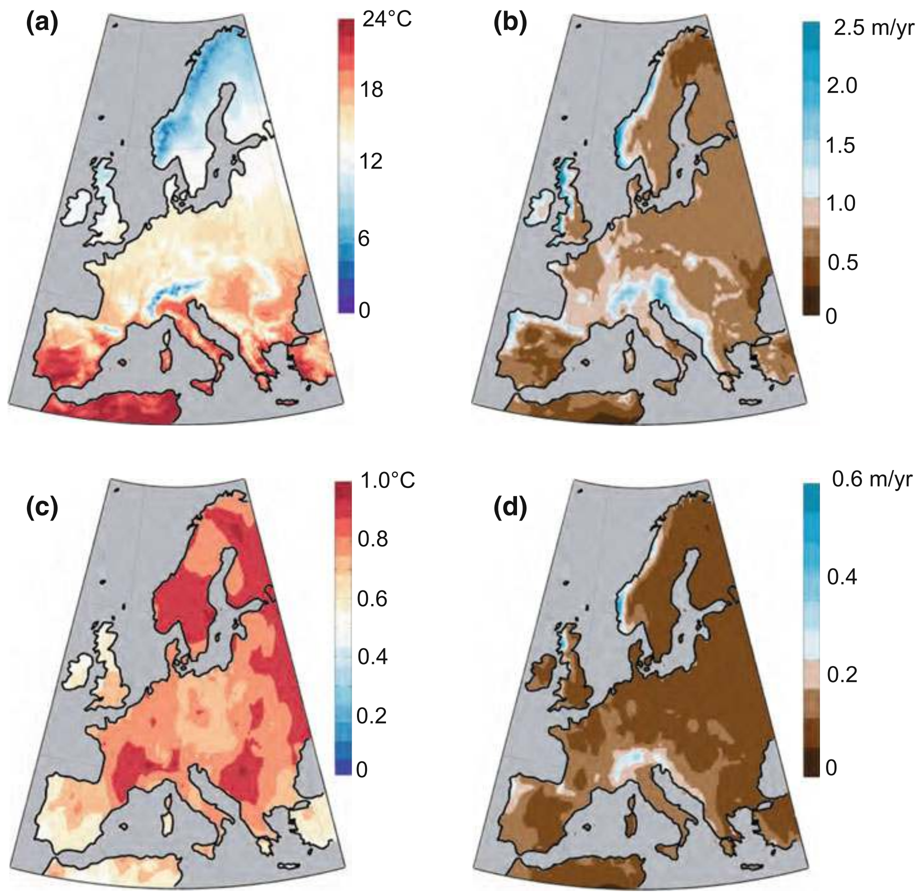

Fig. 2 Climate means and variability over the European continent: **a** mean melt-season (JJAS) temperature (°C), **b** mean annual precipitation (m year^{-1}), **c** interannual standard deviation of melt-season temperature (°C), and **d** interannual standard deviation of annual precipitation (m year^{-1})

where the time series is discretized into $\Delta t = 1$ year increments. a_1 is the lag-1 autocorrelation coefficient and reflects how x_t depends on its value at the previous time step, u_t is a Gaussian, white noise process with unit variance, and a_0 is the standard deviation of the noise term.

Equation (1) represents a system with a single relaxation timescale, τ_c, which is related to a_1 by:

$$a_1 = 1 - \frac{\Delta t}{\tau_c} \approx e^{-\frac{\Delta t}{\tau_c}}, \tag{2}$$

where the approximation holds in the case that $\tau_c \gg \Delta t$. τ_c can be interpreted as the persistence, or physical memory, present in the system. We use the ARFIT algorithm from Schneider and Neumaier (2001) to calculate τ_c for both melt-season temperature and annual precipitation data. In a later section we address the adequacy of Eq. (1) by evaluating if more complicated autocorrelation structures are present in the data.

The data are linearly detrended before being fit to Eq. (1), which is necessary and appropriate for two reasons: (1) there is an established anthropogenic influence on climate, and this must be removed to isolate the natural variability, and (2) persistence cannot be formally determined from a time series with a trend. While it is of course possible that some of the trend is due to natural and not anthropogenic causes, this would still only represent a small fraction of the overall variance in the time series. Moreover, our assumption of a linear trend is a conservative treatment of the data–it is known that the anthropogenic forcing is not linear, especially through the 20th Century and over Europe (e.g., Forster et al. 2007). We expect, therefore, that removing only a linear trend means that some of the low frequency variability remaining in the time series is attributable to anthropogenic climate forcing.

Figure 3a, b show τ_c for melt-season temperature and annual precipitation. Across most of Europe, both climate fields have values of τ_c less than one year, and as such are not statistically different from zero. Therefore, for this 100-year period, much of the variability in these climate fields throughout Europe is consistent with simple white noise. The exception to this picture is in Southern Europe, where melt-season temperatures have values of τ_c between 1 and 1.5 years. As we subsequently show, this small amount of summertime memory is found in both the longer-term individual weather station records and also the glacier mass balance data. We're not aware of any explanation of this summertime persistence, but it appears to be a robust feature of the climate in the region.

Our overall conclusion is that substantial persistence in these climate fields cannot be established from this

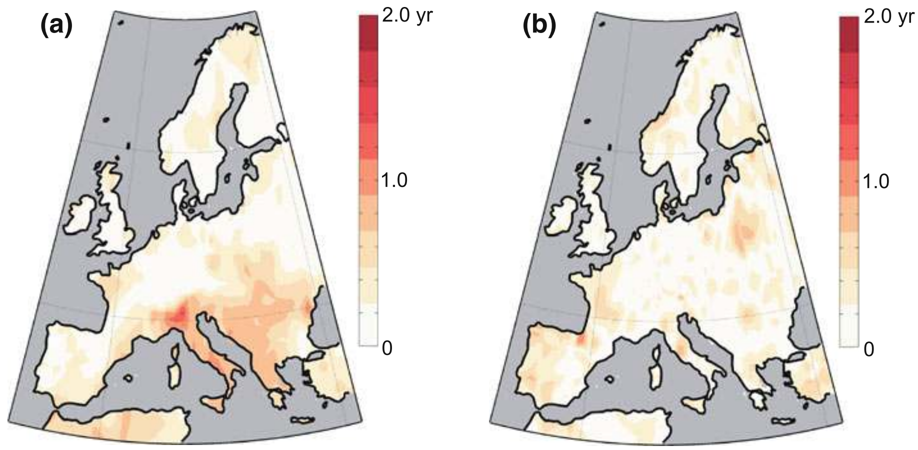

Fig. 3 τ_c (years) calculated from fitting the simple persistence model in Eq. (1) to **a** melt-season temperature; and **b** annual precipitation time series data

100 year-long gridded dataset. The small values of τ_c also mean that the persistent component of climate variability constitutes only a small fraction of the total variability in these climate time series. From Eq. (2), the fraction of the variance attributable to persistence is equal to a_1^2, or $e^{-2\frac{\Delta t}{\tau_c}}$.

These timescales might perhaps seem surprisingly short in the context of such widely promulgated phenomena such as the Atlantic Multidecadal Oscillation (AMO, e.g., Delworth and Mann 2000). It is important to note that the AMO is an index of sea-surface temperatures (SSTs), which do exhibit persistence. However SSTs are only one influence on meteorological variables and, in fact, the near-absence of interannual persistence in atmospheric variables is well known in the climate community (e.g., Wunsch 1999). A sense of what these short decorrelation times mean is presented in Fig. 7, which shows the autocorrelation functions for a variety of climate indices relevant for glaciers. The final section of this paper includes more discussion of the issues.

3.2.2 Higher-order autoregressive models

The advantage of the simple model described above is that it can be identified with a single and readily interpretable timescale. However, it may also under-fit the autocorrelation structure, and thus not properly capture the persistence present in the data. A more complete analysis can be performed using a general, pth-order, autoregressive model (hereafter referred to as AR-p):

$$\begin{aligned} x_t &= a_1 x_{t-\Delta t} + a_2 x_{t-2\Delta t} + \ldots + a_p x_{t-p\Delta t} + a_0 u_t \\ &= \sum_l a_p x_{t-p\Delta t} + a_0 u_t, \end{aligned} \tag{3}$$

where a_p represents the autoregressive coefficient at lag-p, and a_0 and u_t are as already defined. An AR-p process represents a pth order differential equation, and so supports a combination of oscillatory and exponentially-decaying solutions. The model represented by Eq. (1) is thus an AR-1 process ($p = 1$). Additional coefficients will always improve the fit of the model to the data, even if there is no physical significance to that improvement. To account for this, higher-order models are penalized relative to lower-order models. The ARFIT algorithm uses either of two standard criteria for this penalty: Akaike's Final Prediction Error (FPE) and Schwarz's Bayesian Criterion (SBC) (e.g., Schneider and Neumaier 2001). We favor the SBC, which penalizes higher order processes more strongly than FPE. We do so because the meaning of those more complicated oscillatory and exponential combinations is unclear and of doubtful physical significance—nonetheless we report results obtained for both criteria. Finally, the residuals u_t are checked using a Kolmogorov–Smirnov test (e.g., von Storch and Zwiers 1999) to verify that they are consistent with Gaussian white noise. The algorithm thus identifies the AR-p process that is a complete and also a self-consistent description of the data.

Figure 4a shows a histogram of the values of p—these represent the best-fit autoregressive process for both melt-season temperature and annual precipitation at each grid point. AR-0 (white noise) and AR-1 are by far the most prevalent, and between them account for 92.9 % of the total grid points in melt-season temperature and 99.8 % in annual precipitation (70.8 and 82.7 % respectively using FPE criterion). Only a combined 1.4 % of cells (16.1 % using the less-strict FPE criterion) are described by processes of third order or higher. It is not clear whether these higher-order processes have some physical importance, or are merely the result of statistical fluctuations. The majority of the higher order processes in melt-season temperature occur in southern Europe, where some unusual persistence in summertime memory has already been noted.

The coefficients of the autoregressive equation can be related to the oscillatory periods and exponential decay times of the solutions to the underlying differential

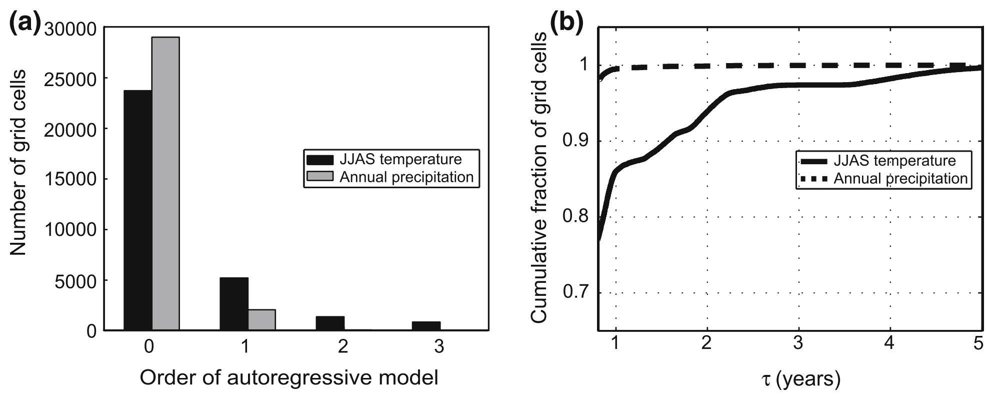

Fig. 4 **a** Histogram showing the distribution of p's for the best-fit AR-p process at every grid point; **b** The cumulative fraction of grid cells characterized by decorrelation timescales less than or equal to τ

equation (e.g., von Storch and Zwiers 1999). Because persistence is our focus here and because the vast majority of coefficients are not associated with oscillations (see above), we present the statistics of the decay timescales in Fig. 4b. Over 90 % of grid cells have melt-season temperature decay timescales of 2 years or less, and 98 % of grid cells have annual precipitation decay timescales of one year or less. We thus emphasize that even the small amount of persistence that is identified in this dataset is associated with timescales that are much less than decades. We will return to this point in the discussion, but it is important to be clear about the logic of the analysis here. This does not formally prove the absence of long-term persistent fluctuations in the climate in Europe. It does, however, demonstrate that if persistence does exist within this 100-year long record, it makes up only a small fraction of the observed variability.

Finally we note here that an AR(p) process is not the only method for characterizing persistence in a time series. The final section of this paper discusses some of the alternatives.

4 Implications for glaciers

4.1 Linear glacier model

Any time series can be split into a persistent component that depends on previous time steps (i.e., $\sum a_p x_{t\text{-}p\Delta t}$ in Eq. 3), and a component that is due to white noise (i.e., $a_0 u_t$ in Eq. 3). By partitioning each climate time series in this way, we can formally attribute glacier behavior to either white noise or persistence in the system and determine the relative importance of these two components for driving glacier variability.

Following in the spirit of Johannesson et al. (1989), Roe and O'Neal (2009) derived a geometric linear model to characterize the magnitude of glacier length response, $L'(t)$, to variations in melt-season temperature, $T'(t)$, and annual accumulation, $P'(t)$. The terminus position is described by the first-order ordinary differential equation:

$$\frac{dL'(t)}{dt} + \frac{L'(t)}{\tau_G} = \alpha T'(t) + \beta P'(t). \tag{4}$$

τ_G is the timescale on which the glacier relaxes back to its equilibrium length (often referred to as the glacier 'memory'). α and β are coefficients that are related to the glacier geometry and mass balance parameters.

From the discretized form of Eq. (4), the variance of glacier length excursions can be written as

$$\sigma_L^2 \frac{\tau_G}{2\Delta t}\left(\alpha^2\sigma_T^2 + \beta^2\sigma_P^2\right) = \frac{\tau_G}{2\Delta t}\sigma_c^2, \tag{5}$$

where σ_c^2 is the variance of the combined climate time series

$$C(t) = \alpha T'(t) + \beta P'(t). \tag{6}$$

The combined forcing, $C(t)$, can also be modeled as an AR-p process.

The relative importance of the persistent and white noise components for driving the glacier variability can be determined by forming the ratio:

$$R = \frac{\sigma_{L_{wn}}^2}{\sigma_L^2}, \tag{7}$$

where $\sigma_{L_{wn}}^2$ is the variance of length that occurs due to the white noise component of the climate forcing, $\sigma_{c_{wn}}^2$, and σ_L^2 is the variance of length in response to the full climate forcing, σ_c^2. From Eq. (5), this can be rewritten as:

$$R = \frac{\sigma_{c_{wn}}^2}{\sigma_c^2}. \tag{8}$$

In other words, R depends on glacier parameters only via the influence of α and β in Eq. (6).

Standard textbooks (e.g., Box et al. 2008) relate the variance of a general AR-p process to the variance of the white noise, from which the total variance of our climate time series can be written as:

$$\sigma_c^2 = \frac{\sigma_{c_{wn}}^2}{1 - \sum_{i=0}^{p} a_i \rho_i}, \tag{9}$$

where ρ_p is the autocorrelation coefficient at lag-p. Note that, in contrast to Eq. (1), it is generally not true that $a_p = \rho_p$, except when $p = 1$. The ratio from Eq. (8) reduces to a simple and elegant form:

$$R = 1 - \sum_{i=0}^{p} a_i \rho_i. \tag{10}$$

Thus, for specified glacier geometry and mass balance parameters, we can calculate the relative importance of white noise in the climate system in driving the variance of glacier fluctuations in Europe. We use values of $\alpha = 75$ m °C^{-1} and $\beta = 160$ years, which were derived by Roe and O'Neal (2009) as typical for a small (i.e., a several kilometer-long) mid-latitude glacier. Our results are not especially sensitive to these parameters. Figure 5 shows R for the best-fit AR-p process at each grid point. The vast majority of the variance in glacier length is attributable to the white noise climate forcing. While our gridded analyses can only be applied to the period this dataset covers, we next evaluate some longer individual station records and some direct glacier mass balance records to see if the same conclusion holds true.

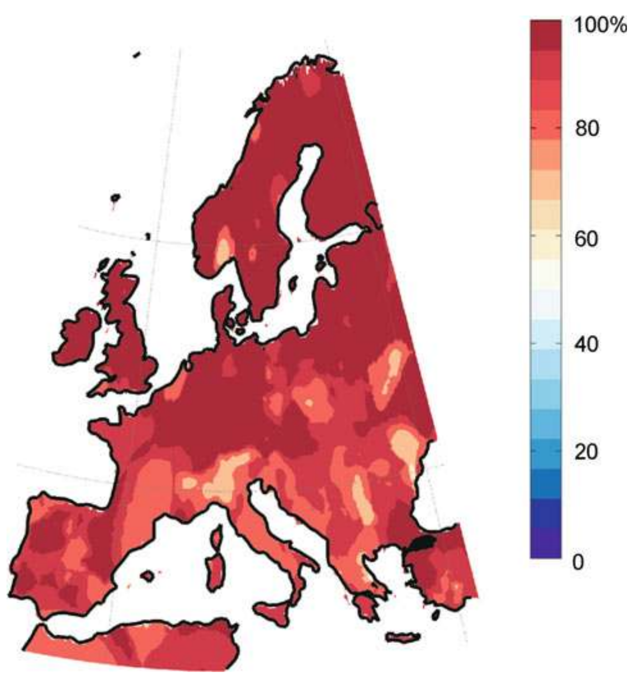

Fig. 5 The percentage of the predicted natural glacier variance that is due to the interannual climate variability (i.e., R in Eq. 10), calculated using gridded climate data and the simplified glacier model described in the text. For ease of presentation, the percentage is shown for each grid point regardless of whether a glacier exists or not. The figure demonstrates that the variance in glacier length is dominated by the interannual component of climate variability

4.2 Other datasets

In this section, we characterize the persistence in selected individual meteorological station records and glacier mass balance records. These longer datasets might identify persistence that could not be detected in the 100-year gridded data. Although shorter in duration, we also analyze the glacier mass balance records; which provide the most direct observations available of the climate the glacier actually experiences.

4.2.1 Long-term temperature records

We analyze seven long-term (≥180 years) melt-season temperature records from stations that were chosen for their proximity to either the Scandinavian Mountains or the Alps. We are not aware of comparably long precipitation data, although the results from the previous section suggest that precipitation variability has little interannual persistence.

The results are presented in Table 1. All records from both Scandinavian and Alps regions show τ_c equal to less than one year—consistent with the results from the gridded dataset (Fig. 3). The best-fit autoregressive model to the data and the corresponding percentage of the total variance due to white noise is also presented in Table 1. The records from Scandinavia are all fit best with pure white noise (AR-0). Mediterranean station data indicate a more complicated regional autoregressive structure, as the majority of their time series are best described by higher-order autoregressive models. Again, this pattern is similar to the results found in the previous section. Despite this regional summertime temperature persistence, calculations using Eq. (10) demonstrate that the interannual variability again dominates the total variability of the climate forcing (last column, Table 1).

4.2.2 Mass balance records

Unfortunately, there are only a limited number of glaciers with annual mass balance observations extending longer than thirty years, and even fewer with seasonal mass balance monitoring. Nonetheless, these records are a direct measure of the climate forcing actually influencing the glacier.

Twenty-two mass balance records were examined from the database kept by the World Glacier Monitoring Service (Dyurgerov 2002). The results for annual mass balance are shown in Table 2 and are again in agreement with our earlier analyses: all but two of the annual mass balance records are fit best with pure white noise (AR-0). The two exceptions are The Great Aletcsh Glacier and The Brøgger Glacier. The former is located in the Alps, where the observed summertime persistence may be influencing a

Table 1 An analysis of the persistence in melt-season temperature from eight long-term (>150 years) instrumental records

Name of weather station	Country	Source	Length of temperature record (years)	τ_c (years)	Best-fit AR-p		Percent of total variance due to white noise	
					SBC	FPE	SBC	FPE
Stykkisholmur	Iceland	RIMFROST	180	0.67	1	4	94.7	90.8
Oslo	Norway	RIMFROST	194	0.41	0	0	100.0	100.0
Uppsala	Sweden	RIMFROST	236	0.56	0	8	100.0	90.7
Stockholm	Sweden	RIMFROST	250	0.51	0	3	100.0	96.2
Kremsmuenster	Austria	Met-UK	234	0.28	0	0	100.0	100.0
Innsbruck	Austria	Met-UK	223	0.88	2	2	86.1	86.1
Geneve	Switzerland	RIMFROST	257	0.80	3	4	83.4	82.6
Milano	Italy	RIMFROST	247	0.98	2	3	80.3	79.0

The last five columns show the decorrelation time, the best-fit AR-*p* process based on two different criteria, and the fraction of the variance attributable to interannual variability. See text for details. Data available at http://www.rimfrost.no/ and by request from http://www.metoffice.gov.uk/weather/europe/

complex autoregressive model fit. The latter stands out as unique—despite being fit with a complicated autoregressive structure (AR-5), The Brøgger exhibits no persistence when modeled as an AR-1 process (i.e., $\tau = 0$ year).

Twelve of the above glaciers also had seasonal mass balance records available. We found that there was no persistence in any of the wintertime mass balance data, but a small amount of persistence was found in the summertime mass balance of the two Svalbard glaciers as well as the Sarennes Glacier in the Alps. The long-term station data and the glacier mass balance records therefore corroborate our findings from the gridded dataset: it is hard to establish the presence of any statistically significant persistence in these climate records, and if it does exist, it represents only a small fraction of the climate forcing experienced by the glaciers.

Table 2 Long-term (>30 years) observational annual mass balance data for glaciers in Europe

Name of glacier	Country/region	Length of mass balance record (years)	Best-fit AR-p		τ_c (years)
			SBC	FPE	
Austre Brøggerbreen*	Svalbard	32	5	5	0.00
Midre Lovenbreen*	Svalbard	31	0	5	0.00
Storglaciaren*	Sweden	52	0	1	0.55
Engabreen*	Norway	34	0	9	0.00
Alfotbreen*	Norway	41	0	0	0.36
Hardangerjokulen*	Norway	41	0	0	0.00
Storbreen*	Norway	55	0	0	0.45
Hellstugubreen*	Norway	42	0	0	0.28
Grasubreen*	Norway	42	0	0	0.16
Nigardsbreen*	Norway	42	0	0	0.00
Sarennes*	Alps	47	0	0	0.56
Hintereis*	Alps	45	0	0	0.65
St. Sorlin	Alps	45	0	0	0.53
Limmern	Alps	42	0	0	0.51
Plattalva	Alps	42	0	0	0.47
Gries	Alps	40	0	0	0.00
Silvretta	Alps	42	0	0	0.52
Great Aletch	Alps	50	1	3	0.55
Kesselwand	Alps	44	0	0	0.59
Vernagtf	Alps	39	0	0	0.56
Sonnblickk	Alps	43	0	0	0.36
Careser	Ortles-Cevedale	34	0	0	0.34

An asterisk next to a glacier name indicates seasonal mass balance data are also available. Decorrelation times (τ_c) are calculated by fitting a first-order autoregressive model to the time series

5 Spatially coherent patterns of European climate variability

For the records we've examined, some of which extend back more than two centuries, we have evaluated the *temporal coherence* of the climatic variability relevant for glaciers. Our analyses suggest that temporal coherence is low, and that the interannual component dominates. Nonetheless, if all glaciers within a region behaved in the same way, would that indicate that a climate change was responsible? In other words what is the *spatial coherence* of the patterns of natural climate variability? A useful rule of thumb is that atmospheric variability is highly coherent on the spatial scale of a Rossby radius—typically 1,000–2,000 km in the midlatitudes (e.g., Wallace and Hobbs 2006). Thus, glacier variability within regions on that scale is expected also to be highly coherent, even without a climate change (e.g., Huybers and Roe 2009). For the gridded dataset spanning 100 years, we use a standard empirical orthogonal function (EOF) analysis (e.g., von Storch and Zwiers 1999) to calculate the dominant spatial patterns of variability in annual precipitation and melt-season temperature. The data are linearly detrended prior to calculating the EOFs, as our purpose is to evaluate the natural variability in the system. Without detrending, the first EOF of temperature is a Europe-wide warming, consistent with anthropogenic climate change.

The first three EOFs of melt-season temperature are shown in Fig. 6a–c. The EOFs explain 35.5, 19.2, and 18.3 % of the variance, respectively. The first EOF is characterized by a fairly uniform pattern across the continent, maximizing in the center of Western Europe with relatively low amplitude near coasts. EOF2 is a north–south dipole pattern, and EOF3 has an east–west dipole structure.

The first three EOFs of the annual precipitation are shown in Fig. 6d–f—they explain 21.7, 13.5, and 7.2 % of the variance, respectively. The first EOF is a north–south dipole. This is the classic signature of the North Atlantic Oscillation, and reflects either a northward or southward displacements of the storm track (e.g., Hurrell 1995). The physical interpretation of the other two EOFs is less straightforward, and may just reflect noise.

The basic result from this spatial analysis is that climate variability is highly coherent on the scale of the European Alps or of Scandinavia. Thus, one should expect glaciers within those regions to also be highly coherent—even for populations of glaciers with widely varying geometry (see Huybers and Roe 2009; Marzeion and Nesje 2012). Therefore, these individual glaciers do not represent independent information about climate. One might expect Scandinavian glaciers to vary independently from those in the Alps, and thus, if the glaciers in the two regions covaried with each other, two pieces of information about climate could be combined. It is worth noting that many studies have established that the pre-anthropogenic era behavior of Scandinavian glaciers is not, in fact, coherent with that of the Alps over the last few centuries (e.g., Nesje and Dahl 2003; Nesje et al. 2007). This is consistent with the glaciers being driven by natural variability rather than by some large-scale climate forcing with a uniform sign, such as the direct effects of solar luminosity. However, the climatic response to a volcanic forcing is not uniform (e.g., Robock 2000) and therefore might also be consistent with asynchronous glacier advances. A more formal analysis of the degrees of freedom in these climate patterns

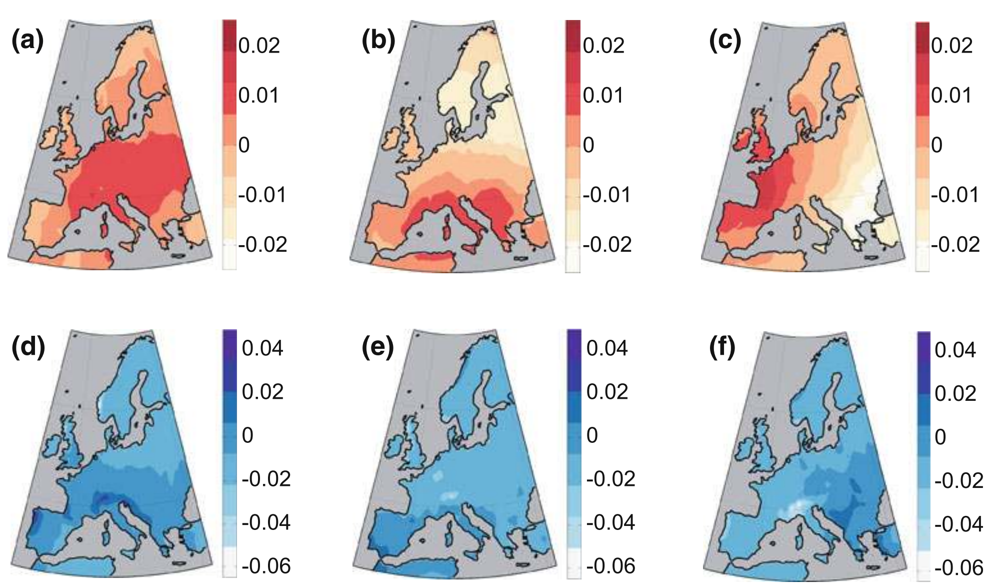

Fig. 6 **a**–**c** The first three EOFs of the melt-season temperature explaining 35.5, 19.2, and 18.3 % of the variance, respectively; and **d**–**f** The first three EOFs of the annual precipitation, explaining 21.7, 13.5, and 7.2 % of the variance, respectively

(both space and time) could be done employing the method of Bretherton et al. (1999).

6 Summary and discussion

Several recent studies have pointed out the importance of stochastic climate variability for driving glacier fluctuations. Here, we've sought to characterize the relative importance of interannual versus persistent climate variability over Europe for the atmospheric variables most relevant to glaciers.

Using: (1) a Europe-wide, century-long dataset; (2) longer records from individual stations; and (3) direct records of glacier mass balance, our results suggest that glaciers experience a climate that is characterized by very little persistence. Decorrelation timescales—a simple measure of memory in the system—are generally less than a year for all datasets, which suggests that interannual variability dominates the climate forcing. The exception to this is some slight persistence in summertime temperatures over southern Europe, which is a robust feature in all three datasets examined. We are unaware of any existing explanation for this.

Given the prominent attention paid to the Atlantic Multidecadal Oscillation (AMO, e.g., Huss et al. 2010; Chylek et al. 2011), it is perhaps surprising that we identify so little persistence in climate over Europe. The AMO index from the National Oceanographic and Atmospheric Administration is constructed from the weighted average time series of Atlantic sea surface temperatures (SSTs) from 0 to 70 N, detrended, and (optionally) has a 121-month smoother applied. The physical interpretation of the AMO as a mode of natural climate variability is controversial. Some analyses interpret it as a natural phenomenon (e.g., Delworth and Mann 2000; Zhang 2008). Others argue that it is a result of anthropogenic climate forcing, and caused by the non-monotonic impact of aerosols (Crowley 2000; Mann and Emanuel 2006; Shindell and Faluvegi 2009; Booth et al. 2012). In particular, aerosols are thought to have played an important cooling role during the rapid industrialization post-World War II, and their reduction following the Clean Air Act in the 1970s is associated with a resumption of a stronger warming trend. A good review of decadal variability can be found in Deser et al. (2010).

No matter what the cause, it is established that the instrumental record supports the existence of some persistence in North Atlantic SSTs (though it is perhaps better described as multi-annual rather than multi-decadal). However that persistence is not imparted without modification onto meteorological variables over Europe, for which the upwind SSTs are only one influence.

This is illustrated in Fig. 7, which shows lag correlation plots for long records of several climate indices. Persistence is clearly present in the AMO index. We pick June through September, months that have most relevance for the glacier melt season, but the results do not depend on that choice.

However, for the North Atlantic Oscillation (NAO), an index of sea-level pressure above the North Atlantic, Fig. 7 shows there is little evidence of persistence (see also e.g., Wunsch 1999). Therefore it is clear that persistence in SSTs does not transfer directly to the overlying atmospheric pressure. Variability in the NAO has been often been invoked as contributing to the variability in glacier mass balance (e.g., Nesje and Matthews 2012; Imhof et al. 2012). Since the instrumental record of the NAO does not exhibit significant persistence, these studies would support the contention that interannual variability is the dominant driver of glacier fluctuations.

The same autocorrelation plots can be used to elucidate our results from prior sections: it is clear in Fig. 7 that neither the 190-year record of summertime temperatures from Oslo, nor the 50-year annual mass-balance record from Storbreen glacier exhibit significant persistence on interannual timescales. These last two curves serve to illustrate why the $AR(p)$ analyses of earlier sections return such short decorrelation times, and also demonstrate that the results are not an artifact of the analysis method.

Our results establish that, consistent with other studies, the instrumental climate and mass balance records do not support significant persistence in melt-season temperature and annual precipitation (except in a few areas). For example, Reichert et al. (2002) find $\tau_c < 1$ year for the climate near Rhonegletscher, Switzerland, and $\tau_c \sim 1.5$ years for Nigardsbreen, Norway, based on climate model output.

We also note that many studies apply multi-year smoothing filters to both instrumental and paleoclimate time series. While filtering may be necessary because of proxy resolution or dating uncertainties, it can impart an unjustified impression of persistence where none may in fact exist. The poor filtering properties of running means are well known. One must be careful not to infer that power at low frequencies in the spectrum, or prolonged excursions from the mean in smoothed data, necessarily implies real climatic persistence (and therefore predictability) at those timescales.

Lastly, we've modeled climate persistence using an autoregressive analysis (i.e., Eq. 3). While such an analysis aims to directly characterize the autocorrelation structure, there are alternatives. Some studies characterize paleoclimate proxy records with power-law spectra, where power increases towards low frequencies (e.g., Pelletier 1997; Huybers and Curry 2006). This is consistent with the power spectrum expected from a quasi-diffusive ocean heat

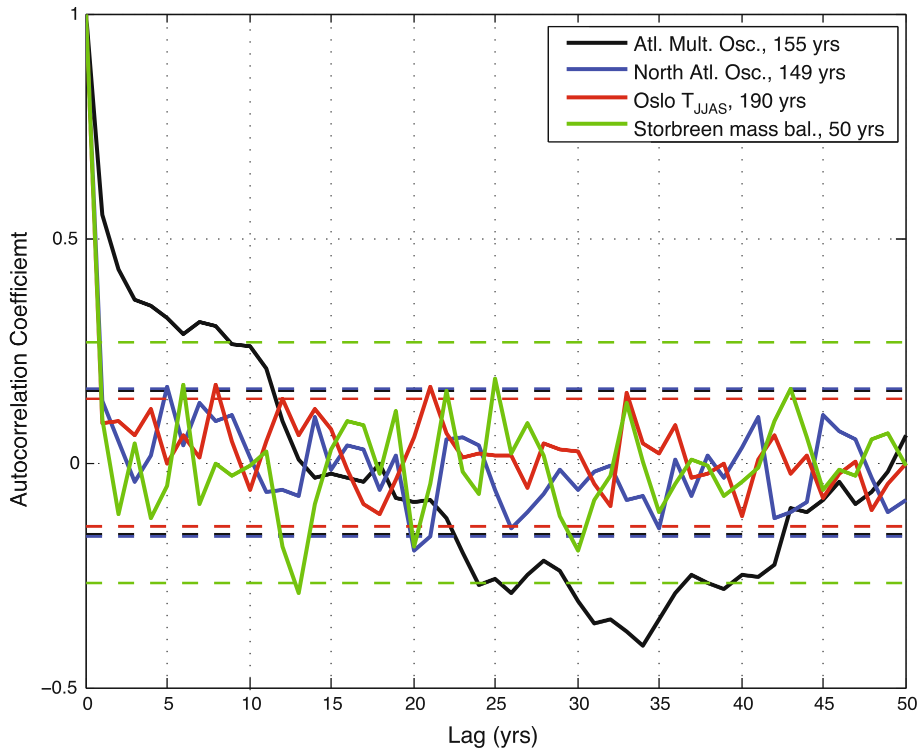

Fig. 7 Autocorrelation plots for four climate indices. The *dashed horizontal lines* provide the 95 % confidence bounds for the respective indices. Autocorrelations outside of the bounds indicate the presence of persistence. The *black line* is 155 years of the Jun–Sept average of the Atlantic Multidecadal Oscillation index (available from NOAA at http://www.esrl.noaa.gov/psd/data/timeseriesimeseries/AMO/). *Blue* is the 149 years of the Nov–Mar index of the North Atlantic Oscillation index (available from NCAR at http://climatedataguide.ucar.edu). *Red* is 190 years of the Jun–Sept summertime temperature in Oslo, Norway (available from http://www.rimfrost.no/). *Green* is 52 years of the annual mass balance record from Storbreen glacier (available from the Worlwide Glacier Monitoring Service: http://www.geo.uzh.ch/microsite/wgms/dataexp.html). All time series were linearly detrended. The confidence limits for the AMO and the NAO plot over each other because the time series are nearly the same length

uptake (e.g., Hoffert et al. 1980; Hansen et al. 1985; Pelletier 1997; Fraedrich et al. 2003). The autocorrelation functions of power-law spectra do not decline to zero with increasing lag as rapidly as an AR-1 model, implying the potential presence of some climate persistence at longer lags. Percival et al. (2001) conclude that an AR-1 model and a power-law spectrum model were equally good fits to a 150-year time series of Pacific climate variability, and that centuries of data would be required to formally discriminate between the two models. The impact of power-law climate variability on glacier length fluctuations is addressed in Roe and Baker (2013).

What role has interannual climate variability played in driving the behavior of European glaciers in the recent few centuries? There can be little serious doubt that the warming associated with anthropogenic climate change has led to the widespread retreat of glaciers during the last 50–100 years. However, prior to that, the situation is less clear. For example, Reichert et al. (2002) modeled the response of Scandinavian and Alpine glaciers to natural climate variability, and concluded that 'Little Ice Age'-scale events would happen every few hundred years, even in a constant climate. Interannual, uncorrelated variability must surely account for some part of the lack of synchronicity between Scandinavian and Alpine glaciers in the eighteenth and nineteenth century (e.g., Nesje and Dahl 2003; Nesje et al. 2007), and elsewhere extending through the Holocene (e.g., Schaefer et al. 2009). Whether the 'Little Ice Age' as a whole should be seen as the result of external climate forcing from volcanoes and solar output (e.g., Crowley 2000) or instead, the result of interannual or weakly-persistent climate variability that has been integrated by the proxies to produce apparently longer-term fluctuations, is an important and unanswered question. It may well turn out to be a bit of both.

Acknowledgments We are very grateful to Brian Smoliak for his many insights on data acquisition and analyses. E.E.B. acknowledges support received from the NASA Harriett G. Jenkins Predoctoral Fellowship Project.

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