INTERANNUAL TO CENTURY SCALE CLIMATE VARIABILITY IN THE EUROPEAN ALPS*

With 4 figures and 1 table

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Zusammenfassung: Die Klimavariabilität im europäischen Alpenraum auf der Zeitskala von Jahren bis Jahrhunderten

Neue Zeitreihen von Proxydaten und frühen Instrumentenmessungen aus den Alpen erlauben eine präzisere Interpretation der Klimavariabilität sowie der dahinter verborgenen Prozesse. Die Studie zeigt, daß während Phasen mit unterschiedlichen Antriebscharakteristiken (forcings) des Klimasystems spezifische Temperatur- und Niederschlagsanomalien auftreten. So wurde während der schwachen Solaraktivität des Maunder Minimums eine Tendenz zu kalten und trockenen Wintern sowie feuchten Sommern registriert. Nach tropischen Vulkanausbrüchen waren die Sommer mehrheitlich kalt, und in der rezenten Phase der zunehmenden Treibhausgase werden vor allem warme Winter beobachtet. Die Korrelationen zwischen den natürlichen und anthropogenen Forcing-Faktoren und dem Nordatlantischen Oszillationsindex zeigen kein eindeutiges Bild. Immerhin kann festgestellt werden, daß der Index während der trockenkalten Winter des späten Maunder Minimums mit geringer Solaraktivität betont negativ war. Die Vorstoßphasen der zwei betrachteten Alpengletscher sind bedingt durch ein komplexes Temperatur- und Niederschlagsmuster in Winter und Sommer. Es wird vorgeschlagen, diese Vorstoßphasen mit dem englischen Ausdruck "Little Ice Age Type Events" zu benennen.

Summary: New sets of proxy and early instrumental data from the European Alps allow deeper insights into climate variability and its underlying processes on varying timescales. The study indicates that periods with different forcing characteristics show specific temperature and precipitation anomalies: Cold and dry winters as well as wet summers during the low solar activity period of the Maunder Minimum, cold summers after tropical volcanic eruptions and warm winters in the recent period with an increasing greenhouse gas concentration. The relation between periods with a prevailing positive or negative mode of the North Atlantic Oscillation (NAO) and this natural or anthropogenic forcing is very complex. At least it can be stated that the negative or meridional mode of NAO dominated during the low solar activity period with the cold and dry winters of the late Maunder Minimum. The advance periods of the two selected Alpine glaciers are obviously driven by characteristic but varying temperature and precipitation courses during winter and summer. It is suggested to call these periods Little Ice Age Type Events (LIATE's).

1 Introduction

Mountains are very suitable to study climate change because the gradients of the important climatological parameters like temperature, precipitation and air pressure are very accentuated and the mountain obstacles reinforce dynamical processes, such as the formation of strong winds or heavy rain (BLUMEN 1990). The European Alps are an 800 km long and 200 km wide mountain range in Western Europe, whose climate variability is strongly determined by the North Atlantic weather systems (including those in the Mediterranean Sea area) and the thermal influence of the Eurasian land mass with its strong seasonal effects: a large anticyclone over eastern Russia in winter and several more regional heat lows over different areas in summer. Both influences are related to two typical teleconnection patterns, the all year round observed North Atlantic Oscillation NAO (HURRELL 1995) and the more cold season Eurasian Pattern EU (BARNSTON a. LIVEZEY 1987; Fig. 1). Besides the exposition of the Alps to the sensitive interactions between oceanic and continental climate effects (WANNER et al. 1997), this area has a very long tradition in climate research and disposes of some of the longest observed climatological time series in the world. This allows the diagnosis of important processes inducing climatic variability in the decadal to century timescale. The significance of the data sets is limited by their small spatial coverage. Extrapolations to other continents are therefore not possible.

In this paper three time series with different data types are discussed: reconstructions of glacier fluctuations over 3,200 years; calculated temperature and precipitation proxies over 445 years; and early instrumental data covering a period of 178 years. Glaciers in mountain areas are highly sensitive to climate changes and thus provide one of the nature's clearest signals of warming or cooling and/or dry and wet climate periods. The difficulty in using glaciers as climatic indicators lies in the complex chain of processes linking glacier reaction to climatic change. Energy balance fluctuations at the earth's surface result in changes in glacier mass balance – a direct reaction to the climatic conditions (mainly temperature and precipitation). The

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[*] Dedicated to CARL TROLL on the occasion of his 100th birthday

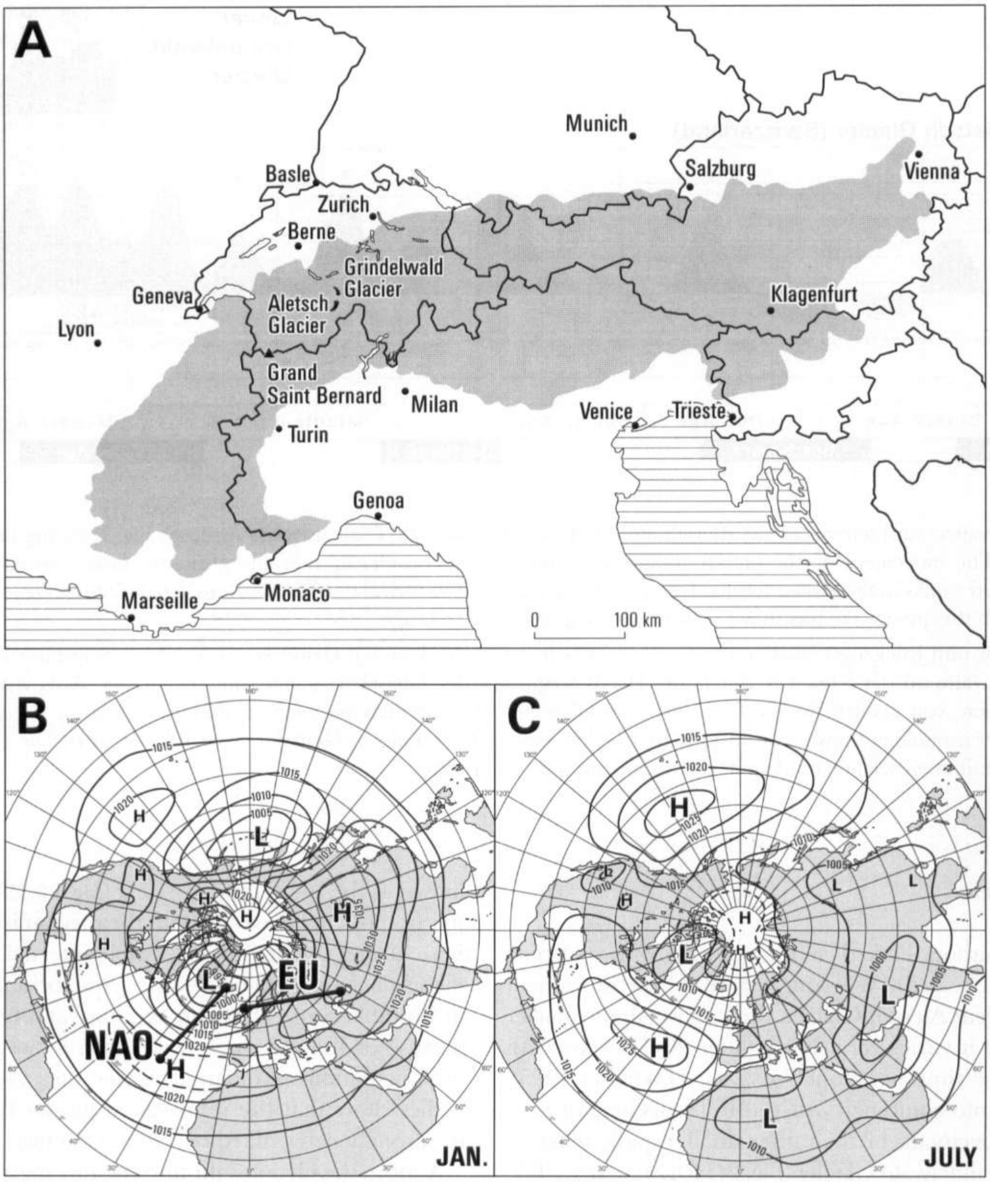

Fig. 1: Geographical and synoptic situation of the European Alps:
a) Topography and important sites
b) Mean sea level pressure over the northern hemisphere during January (1931–1960). The two important teleconnections for Western Europe (NAO, EU; BARNSTON and LIVEZEY 1987) are added
c) Mean sea level pressure over the northern hemisphere during July (1931–1960)

Geographische und synoptisch-klimatologische Situation der europäischen Alpen:
a) Topographie und wichtige Ortsbezeichnungen
b) Gemittelter Bodendruck über der Nordhemisphäre während des Monats Januar (1931–1960). Die zwei für Westeuropa wichtigen Telekonnektionen oder Fernwirkungen des Druckfeldes (NAO, EU; BARNSTON a. LIVEZEY 1987) wurden zusätzlich eingezeichnet
c) Gemittelter Bodendruck über der Nordhemisphäre während des Monats Juli (1931–1960)

resulting change in glacier length (advance or retreat) is an indirect, filtered and delayed signal of these climatic fluctuations. After a certain reaction time, in the case of Alpine glaciers ranging between a few years and several decades, the glacier length changes, finally reaching a new equilibrium after a response time of between several and about 100 years (HAEBERLI 1995; HAEBERLI a. HOELZLE 1995).

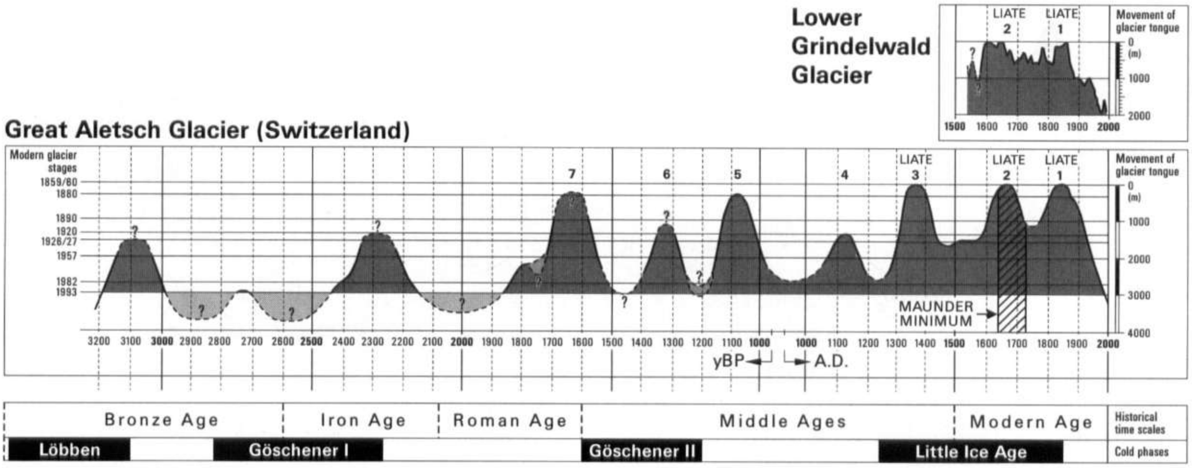

Fig. 2: Advances and retreats of the Aletsch and the Lower Grindelwald Glacier (Swiss Alps; see Fig. 1) during the last 3,200 years. The movement of the glacier tongue was analysed by considering moraine positions, fossil soils (C^{14}), overrun anchored trunks in the glacier forefield (dendrochronology) and historical documents (drawings, paintings etc.). The broken line with the question marks shows periods with a sparse data coverage

Vorstoß- und Rückzugsverhalten des Großen Aletsch- sowie des Unteren Grindelwaldgletschers (Schweizer Alpen; siehe Fig. 1) während der letzten 3 200 Jahre. Die Bewegungen der Gletscherzungen wurden auf der Basis von Moränenpositionen, von fossilen Böden (C^{14}), von vom Gletscher überfahrenen verankerten Baumstrünken im Gletschervorfeld (Dendrochronologie) sowie von historischen Dokumenten (Zeichnungen, Gemälde usw.) rekonstruiert. Die gestrichelten Linien mit Fragezeichen markieren Zeiträume mit spärlichen Daten

2 *Observations*

The authors looked at the records of two Alpine glaciers. The 3,200 year long records of the movement of the Great Aletsch Glacier, the largest Alpine glacier show that it varies very slowly (after 20–30 years with a response time of about 75 years; HAEBERLI 1995). These results combined with the 460 years long records of the movements of the rather small, rapidly reacting Lower Grindelwald Glacier (Fig. 2; HOLZHAUSER 1997) show surprisingly regular, almost periodical fluctuations between glacier hostile (warm/dry) and glacier friendly (cool/wet) periods. Three stronger glacier retreats were observed around 2850, 2550 and 2000 BP which were comparable with the present stage. Phases with positive mass balances and glacier advances occurred around every 200 to 400 years. Even during the Medieval Warm Period (MWP; HUGHES a. DIAZ 1994) a slight glacier advance took place. It is recommended that these quasiregular glacier advances be called Little Ice Age Type Events (LIATE's) because they are typical for the Alpine glacier dynamics within the last 3 millennia. Three striking events (the LIATE's 1–3) were observed during the last 750 years (around 1300–1380, 1570–1640 and 1810–1850), the period known as the Little Ice Age (LIA; GROVE 1988). A first question has to be asked about the mechanisms driving these glacier fluctuations. A simple internal oscillation of the glacier system between an equilibrium stage and an unstable surge or outbreak phase can be excluded because of the very high correlation between the glacier fluctuations at different Alpine sites. Also, several studies show that the represented glacier fluctuations are strongly determined by climate forcing.

A more detailed insight into the low frequency variability of the Alpine climate is possible by using seasonal temperature and precipitation reconstructions for winter and summer (Fig. 3). The monthly temperature and precipitation data had to be determined for a preinstrumental (before 1755), an early instrumental (1755–1860) and the recent instrumental period. Within the period with instrumental measurements, the anomalies were defined as departures from the 1901–1960 mean. The anomalies of the preinstrumental sub-period were estimated from documentary proxy data, from tree-ring data and from descriptive data in historical documents. The values are all expressed in terms of an index of seven discrete levels from –3 to +3 (PFISTER 1995). The lowpass filtered curve shows five distinctive periods each with different climate charac-

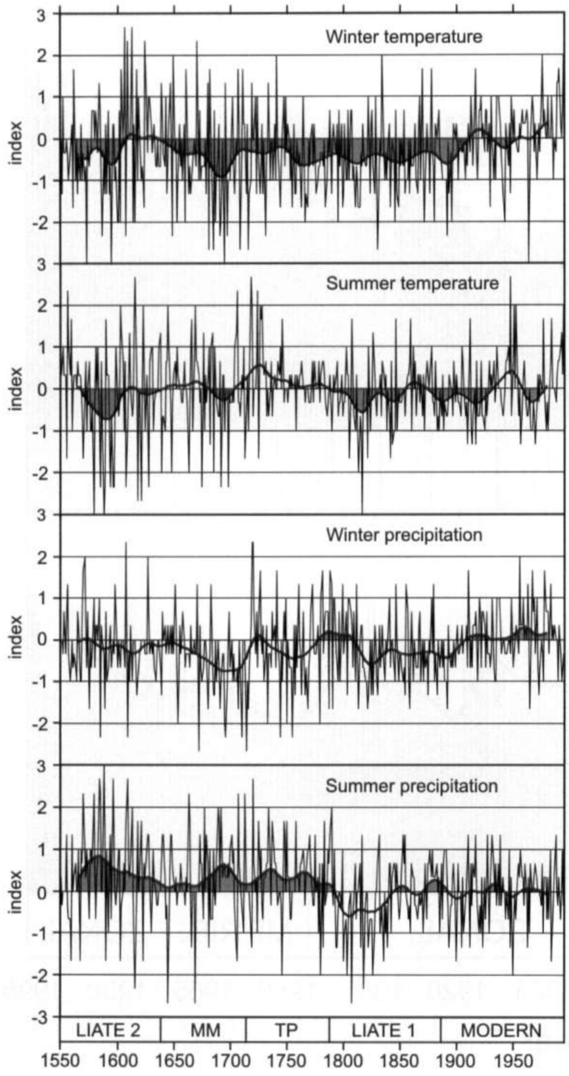

Fig. 3: Annual temperature and precipitation indices for the northern Swiss Alpine foreland between 1550 and 1995 (the determination of the index is described in PFISTER 1995). The black curve represents a low pass filtered mean. The abbreviations of the bar given below are explained in the text

Jahreswerte der Temperatur- und Niederschlagsindizes für das nördliche Schweizer Alpenvorland zwischen 1550 und 1995 (eine Beschreibung der Methodik zur Bestimmung der Indizes findet sich in PFISTER 1995). Die dickere schwarze Kurve zeigt ein tiefpassgefiltertes Mittel. Die Abkürzungen im Balken über den Jahreszahlen sind im Text erläutert

teristics. The first period, representing the end of the second advance of the glaciers in the LIA (LIATE 2), was characterized by low temperatures in both seasons, and wet summers. The summer snowfalls in the higher Alps from 1560 to 1630 must have been an important factor leading to a high albedo and therefore positive mass balances of the glaciers. The second period, called the Maunder Minimum (MM; EDDY 1976) was clearly represented by a very cold and dry continental winter and a rather wet summer climate, a fact which has to be considered in the final discussion of the possible forcing mechanisms. Warm and wet summers, as well as cool and dry winters, were observed during the third transitional phase (TP), which was followed by the fourth period with the last glacier advance of the Little Ice Age in the mid 19th century (LIATE 1 in Fig. 2). The temperatures were in fact low, especially during winter, but precipitation was generally sparse except during the summers after 1840 which were wetter. The climate of the fifth and modern period as shown in Fig. 3 (MODERN), resembles the well-known course of the global climate of the last 100 years.

The detailed dynamics of the last 178 years are represented by the time series of the homogenized annual mean temperature and precipitation series from the high Alpine station Grand Saint Bernard in the western Alps, which has been operated by the monastery since the early 19th century (Fig. 4). The band-pass filtered curve shows significantly positive linear trends for both temperature and precipitation (linear trends: +0.0062 °C · yr^{-1} for temperature and +3.25 mm · yr^{-1} for precipitation). Apart from the last 40 years, the two parameters are more or less anticorrelated because the main precipitation events are mostly related to summertime convective precipitation. Consideration of the central bar between the two curves in Fig. 4 illustrating alternating periods with predominantly zonal and meridional flow regimes (with a high correlation with the NAO index; SCHMUTZ a. WANNER 1998), shows the above discussed subdivision of Fig. 3 into a LIATE 1 and a modern period to be again apparent. The late LIATE 1 period was characterized by progressively lower temperatures and a wet peak around the 1840s which brought enormous amounts of winter precipitation with snow and avalanches (SCHÜEPP 1991). This peak is not very obvious in Fig. 3. Periods with zonal and meridional flow configurations alternated quite clearly, and the fact that a zonal flow regime normally generates higher annual mean temperatures and rather low precipitation amounts over the Alps (WANNER et al. 1997; HURRELL a. VAN LOON 1997) is clearly visible during the 1860s. The modern era can be further divided into three periods with different synoptic regimes. A first zonal phase, with a high frequency of westerlies leading to three temperature and two precipitation peaks, forms the transition from the Little Ice Age to the 20th century

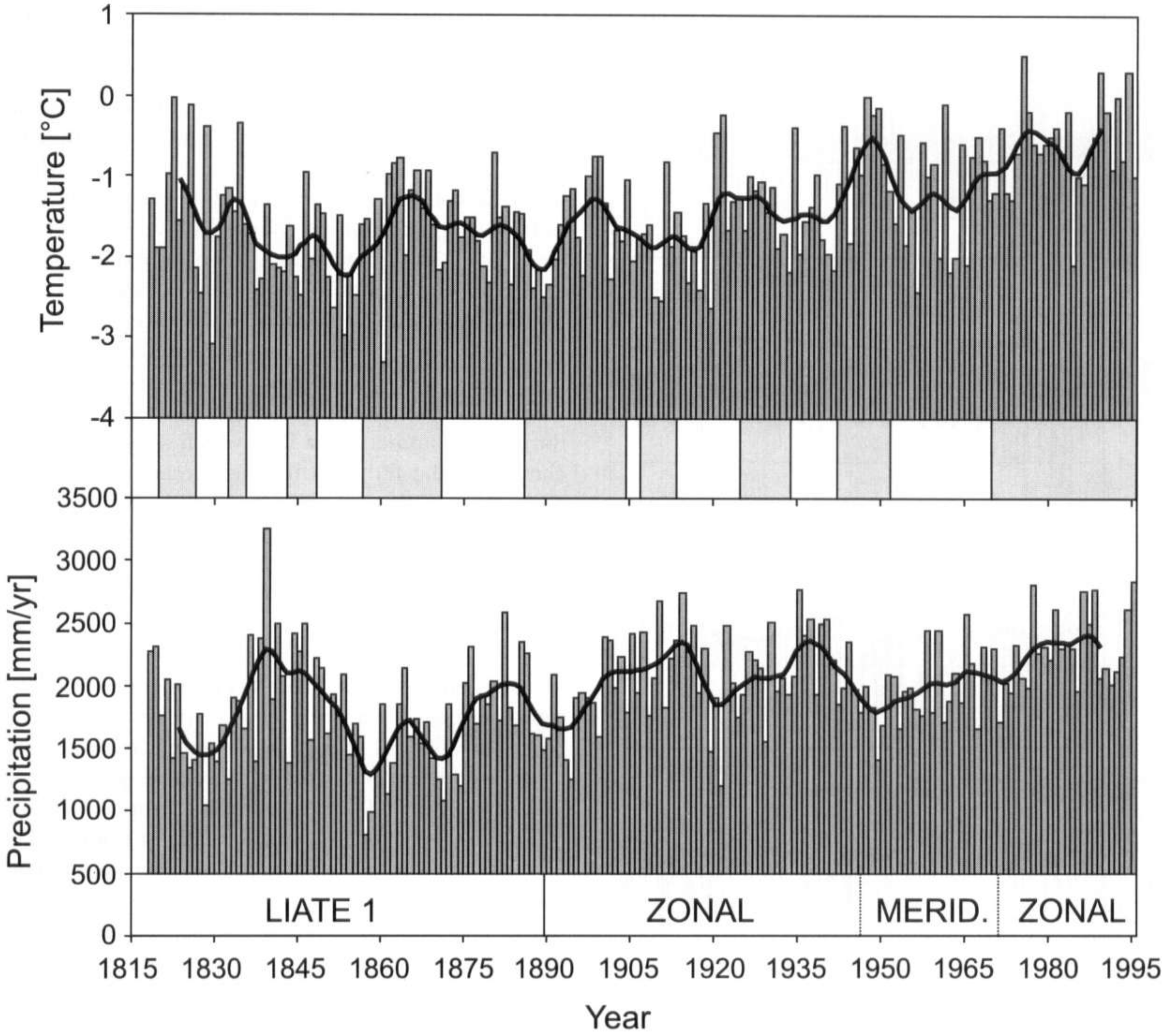

Fig. 4: Mean annual temperature and precipitation curves for the high Alpine station Grand Saint Bernard (2472 m a.s.l.; see Fig. 1). The thick curve represents the bandpass filtered mean. The central bar between the two curves distinguishes between phases with a predominantly zonal (grey sections) or meridional (white sections) flow configuration over Europe (SCHMUTZ a. WANNER 1998). The lower bar subdivides the whole time span into four more or less homogeneous synoptic periods

Jahresmittel für Temperatur und Niederschlag, dargestellt für die hochalpine Station Großer Sankt Bernhard (2472 m über Meer; siehe Fig. 1). Die dicke schwarze Linie zeigt jeweils die tiefpassgefilterten Mittel. Der Balken zwischen den beiden Kurven unterscheidet zwischen Phasen mit vorherrschender zonaler (graue Flächen) oder meridionaler (weiße Flächen) Zirkulationsform über Europa (SCHMUTZ u. WANNER 1998). Der Balken über den Jahreszahlen unterteilt den ganzen Zeitraum in vier einigermaßen homogene synoptische Perioden

warm phase. It was followed by a remarkably homogeneous meridional flow regime between about 1950 and 1974 which brought about a series of snowy winters in the Alps. These winters formed the basis for the optimistic planning of ski lifts and ski resorts along the whole Alpine arc (Fig. 1). This meridional period was followed by the recent and very persistent zonal flow phase (SCHMUTZ a. WANNER 1998). In the Alps, the zonal flow pattern was at least partly responsible for the strong temperature rise of more than 0.6°C which has occurred during the last 60 years. Another surprising phenomenon consists of the strongly increasing annual precipitation amounts, with a positive trend of more than 500 mm or 25% at the Grand Saint Bernard over the last 50 years. Such a high trend was never observed before, and only a minor portion of this

Table 1: Number of anomalous warm/cold and wet/dry seasons during three groups of years with different forcing conditions, determined by using the Pfister indices (PFISTER 1995); n delineates the number of observed years. The number of cases with extreme anomalies is added in parantheses

Zahl der Jahre mit Anomalien von warmen/kalten und feuchten/trockenen Jahreszeiten, dargestellt für drei Gruppen von Jahren mit typischen Antriebs- oder Forcingmechanismen. Die Jahre wurden auf der Basis des Pfister-Index ausgewählt (PFISTER 1995); n bezeichnet die Zahl der berücksichtigten Jahre. Die Zahl der Jahre mit extremen Anomalien wurde in Klammern beigefügt

	Temperature				Precipitation			
	Anomalous winters		Anomalous summers		Anomalous winters		Anomalous summers	
	warm	cold	warm	cold	wet	dry	wet	dry
Explosive volcanic events in the tropics (n = 12)	5 (1)	6 (1)	2	8 (2)	4 (1)	7	5 (1)	5
Low solar activity during the Maunder Minimum (n = 35)	8 (4)	24 (10)	17 (4)	19 (5)	4 (2)	25 (7)	20 (5)	7 (3)
Influence of greenhouse gases, 1959ff. * (n = 32)	20 (5)	6	12 (4)	14 (1)	14 (3)	11 (1)	13 (1)	10 (2)

* periods with strong volcanism excluded

increase can be explained by using synoptic criteria. Therefore, the question about a possible global anthropogenic signal has to be asked in view of the larger set of Alpine stations giving similar signals (WIDMANN a. SCHÄR 1997). The analysed spectra of the two data sets show slightly significant (90% confidence level) peaks at 4.5 and 25 years for temperature and at 45 years for precipitation.

3 Relations to forcing mechanisms

The question posed above about the mechanisms driving the glacier fluctuations has to be supplemented by two additional and important ones: (i) How far was the interannual to century scale climate variability in the Alps influenced by the three most important climate forcing factors (solar activity, explosive volcanism in the tropics, recent greenhouse gas warming) and (ii) what is the influence of this forcing on the zonality of the flow regime and indirectly on the NAO influenced climate? Table 1 gives a rough answer to the first of these two questions. The influence of explosive volcanic events in the tropics was determined by counting the temperature and precipitation anomalies for six periods of two years, all occurring after an explosive volcanic eruption (DAI et al. 1991; BRIFFA et al. 1998) and before the 20th century warming. Eight of the twelve observed summers after these volcanic events are followed by very cold summer and normal winter temperatures, with no precipitation anomalies. Note for instance the low temperatures after the events of 1815 (Tambora, Sunda Islands), 1883 (Krakatau, west of Java) or 1902 (Sta. Maria in Guatemala) in Figs. 3 and 4. This result is physically consistent with modelling studies dealing with the influence of strong aerosol layers on surface climate (GRAF et al. 1993).

During the low solar activity phase of the Maunder Minimum, the winters were very cold and dry, and both the Great Aletsch and the Lower Grindelwald Glaciers show a series of years with a nearly stable or even a negative mass balance (Fig. 2). Based on a spatial analysis of proxy records for western, central and eastern Europe it was possible to demonstrate that the cooling process of this low solar activity period started over the western European continent first, expanded to the east and finally to the thermally slow reacting Atlantic ocean (WANNER et al. 1995). It is imaginable that this wintertime continental cooling is a typical pattern for a longer period with low solar activity, a hypothesis which does not seem to apply to the summer indices of the MM showing normal temperatures and positive precipitation anomalies (Fig. 3; Table 1). Future model studies including feedback mechanisms must continue to analyse this problem.

As a complement to the many modelling studies dealing with the anthropogenic greenhouse effect (IPCC 1996), it was also of great interest to examine the seasonal temperature and precipitation anomalies for the years after 1958. Table 1 shows that only the winter temperatures reveal a clear positive tendency. A positive precipitation anomaly is only visible at selected stations like the Grand Saint Bernard (Fig. 4). It is not actually possible to explain how far these anomalies are caused by circulation changes or by a direct influence of a dry or wet greenhouse effect (ULBRICH a. CHRISTOPH 1999), due to the fact that the two phenomena are complexly coupled together.

4 Influence on the North Atlantic Oscillation

Let us now try to give a rough answer to the second of the above-mentioned questions regarding the influence of the forcing factors on the zonality of the flow over central Europe, and consequently, the two modes of the NAO which affect the Alpine climate in a complex manner. The reason for this complexity is that the Alps are situated in the transition zone between northern Europe (showing warm/wet conditions during the positive, and a cold/dry climate during the negative mode of the NAO), and southern Europe, where almost the opposite reactions apply. At first glance, and after a look at the reconstructions of monthly mean surface pressure maps for the last 300 years (LUTERBACHER et al. 1999), it can be stated that the negative or meridional mode of the NAO dominated during the low solar activity phase of the MM (WANNER et al. 1995) – which led in the Alpine area to a series of cold winters with northeasterly flow and advection of cold continental air. In contrast, a strong tendency to a positive or zonal mode was observed during the last 20 years – which lead to higher temperatures (mainly in winter) and more rain in northern Europe and parts of the Alps. These findings are consistent with the fact that a higher greenhouse gas and a lower stratospheric ozone concentration in the polar area leads to a stronger polar vortex, a strengthening of the zonal flow and a higher frequency of Atlantic storm tracks (ULBRICH a. CHRISTOPH 1999). Speculation therefore remains as to whether or not this vortex was weaker during the MM (as seems possible), and if so why. As concerns explosive tropical volcanism, we can state that these events give rise to increased temperatures in the tropical stratosphere, which in turn increases the meridional temperature gradient and therefore the geostrophic zonal flow of the midlatitudes (GRAF et al. 1993). This fact is probably partly responsible for the negative summer temperature anomalies in the northern Alpine area (Table 1).

5 Possible causes of LIATE's

Let us finally answer the third question concerning the mechanisms driving the glaciers and causing the LIATE's. This answer can only be given in the form of a hypothesis: LIATE's, as it can be deduced by comparing Figs. 2–4, are the result of an overlapping of different glacier-friendly events consisting of cool and wet winters and mainly cool summers and/or autumns with snowfall in the higher Alps. The timescale in Fig. 2 – even for the highly resolved data of the Lower Grindelwald Glacier – shows that glaciers do not linearly react with a certain lag on a single meridional (e.g. around 1880 or 1960) or zonal (e.g. around 1900 or 1990) circulation period (Fig. 4). Very often, a strong meridional circulation resulting from a strong reversal of the positive NAO mode (MOSES et al. 1987), causes extremely cold and dry winters with rather stable or negative mass balances. Therefore, it can be hypothesized that a series of several shorter cool and wet periods is favourable for the mass balances of Alpine glaciers, which are not solely limited by temperature or precipitation. But what is the real physical background behind the Alpine LIATE's? Is it just the normal stochastic behaviour of the atmosphere-sea ice-ocean system? At least one scenario is realistic: If the NAO – in the case of a CO_2-doubling – becomes more positive (zonal regime; ULBRICH a. CHRISTOPH 1999) or remains more or less in a quasi stable positive mode (GRAF et al. 1998), a state which is not absolutely plausible if the ocean is at least partly exerting a determining influence on the NAO (MCCARTNEY 1997), it will have a devastating effect on Alpine glaciers and therefore also on Alpine tourism!

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