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Department of Geography of the Universities of Lausanne and Fribourg, Switzerland

Seasonal Relationship Between Temperature, Precipitation and snow Cover in a Mountainous Region

M. Rebetez

With 4 Figures

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Summary

An analysis of correlation coefficients for climatological data covering the period 1901–1994 or 1931–1994 for six locations in Switzerland has been made in order to highlight the relationships between temperature, precipitation (rain and snow) and snow in summer and in winter. The results show that colder summers tend to be associated with more precipitation, mainly in terms of the frequency of occurrence of precipitation, but also in terms of its abundancy. In winter, sites located at lower altitudes behave differently from those at higher elevations. At lower altitudes, warmer winters tend to be rainier and to have less snow (only a small part of winter precipitation falls in the form of snow). Above 1000–1500 m, correlations between temperature on the one hand, and precipitation or snow on the other, tend to be weaker than at lower elevations; warmer winters are associated with less snow but also with less precipitation in general, while the relationship between precipitation and snow is stronger.

These results confirm that during cold periods of the past, such as Löbben Phase (1400 BC–1230 BC) cold summers were probably linked to frequent and abundant precipitation. These conditions led to increased mortality as well as to population migrations. In terms of potential future global warming, if the current temperature/precipitation relationships remain unchanged, then warmer summers will likely be linked to a decrease in precipitation. Higher winter temperatures can be expected to lead to a general decrease of snow and to a decrease in precipitation, but only at higher elevations; warmer winters would conversely be associated with an increase in precipitation at lower altitudes.

1. Introduction

While there now seems to be a consensus among the climate research community regarding the reality of global climate change (Houghton et al., 1990, 1992), the regional response to climate change is still highly uncertain, in particular because of the relatively crude grid-resolution of even the most advanced general circulation climate models. If we want to be able to forecast potential future climatic changes we need to improve our understanding of current and past climate, not only at the global but also at the regional scales. Historians have contributed to improve this knowledge in recent decades, following the pioneering work of H. H. Lamb (1968) or E. Leroy Ladurie (1967). In the Alpine region, there are a number of data sources which allow detailed climatological studies to be carried out, such as the historical CLIMHIST data base (Pfister, 1985) or the 20th Century Swiss Climate Data Base (Bantle, 1989). However, a major problem arises in the interpretation of historical or proxy data when there is information for either temperature or precipitation but not for both simultaneously; Ornato (1988) has strongly urged climatological research to focus on this problem. In-depth understanding of Alpine climate processes and their possible future evolution would require a clear appraisal of inter-relationships between temperature, precipitation, and snow, three of the major atmospheric variables characterizing climatic regimes in the Alps.

It has been shown that mild winters in boreal latitudes in general result in more snowfall and tend to increase the volume of continental glaciers (Bryson 1994) while, for instance, during the period between 15,000 BP and 6,000 BP, colder winters, associated with warmer summers, characterized a time of rapid wasting of the continental glaciers (Kutzbach et al., 1986). Not much is known, however, about the relationship between winter snowfall and temperature in the Alps, nor about the relationship between winter or summer temperature and precipitation. Temperature exhibits clear warming signals during the 20th Century, at the global as well as at the regional scale (Houghton et al., 1990, 1992). Beniston et al. (1994) have shown that this is also the case in Switzerland; but as far as precipitation is concerned, highlighting a trend in 20th Century data is made very difficult by the high variability of this parameter. The same is true for the analysis of snow amounts.

In other regions of Europe, attempts have been made to correlate temperature and precipitation on yearly time scales. Neumann (1993) has analyzed such data for Budapest and obtains a correlation coefficient (-0.27 for 50 data/years). The result of the Fisher test in this case would be $F = 3.77$ with $n - 2$ degrees of freedom, which means that the correlation is significant at the 99% significance level. According to the critical values of Pearson's product-moment correlation coefficient r, the Null Hypothesis H_0 could be rejected if r were greater than 0.354 (at the 99% significance level) or 0.231 (at the 90% level). This indicates that, although there is a link between temperature and precipitation, the correlation is not very high; the result implies that deriving annual values of precipitation from annual values of temperature is fraught with uncertainty. Although there is no strong relationship between temperature and precipitation on the yearly time scale, there may however exist more significant links on the seasonal time scale. For example, Striem (1974) has shown that in Jerusalem cold winters are usually rainy winters. Brazdil (1994) studied the relationship between temperature and sunshine duration in central and south-eastern Europe and has shown an important increase in sunshine duration associated with the warmest period of the 20th Century, particularly in summer and less so in winter. The search for trends in precipitation is very difficult because of its very high variability (Beniston et al., 1994; Auer et al., 1994).

This paper presents the results of a correlation analysis between temperature, precipitation (here, precipitation refers to the total water amount which falls in the form of rain and/or snow) snow cover and snowfall, taking into account seasonal and altitudinal differences between temperature and precipitation in winter and summer. The analyses have been conducted

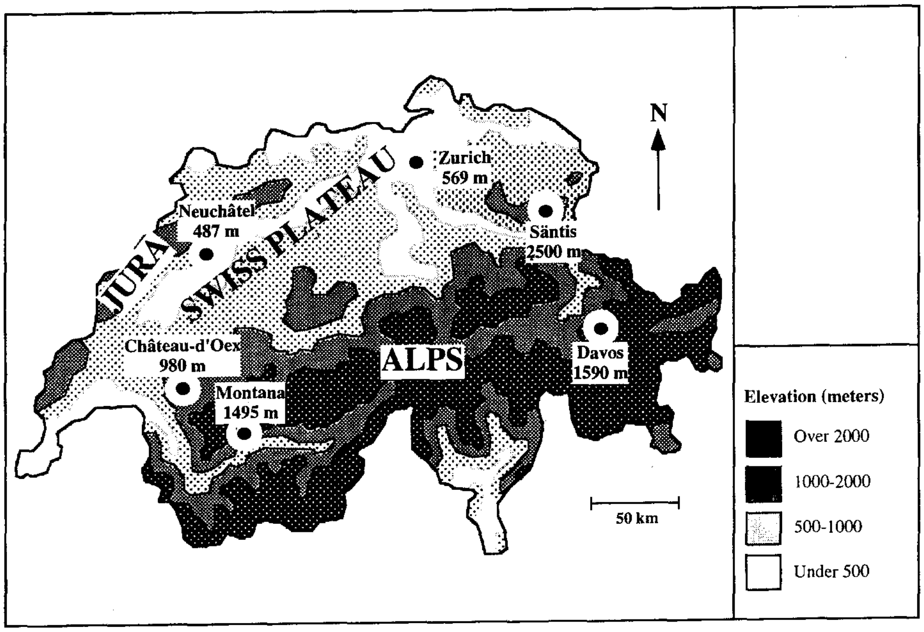

Fig. 1. Map of Switzerland showing the location of the six climatological stations

for six meteorological stations located at different altitudinal levels and in different location types in Switzerland, for the period 1901–1994 or 1931–1994 (this latter series containing daily snow statistics).

2. Parameters and Sites

The definitions of summer and winter employed by the climate research and modeling community have been used here, i.e., respectively June-July-August and December-January-February. Data originate from the Swiss Climate Data Base (SCDB) which comprises daily data since 1901 for the oldset series of sites. Six climatological stations were selected on the basis of the length of their time series, the existence of data for snow depth and amount of snowfall, and also according to their representativity of different altitude levels. The climatological stations are the following:

Neuchâtel, 487 m above mean sea level (1901–1994)
Zurich, 569 m (1901–1994)
Château-d'Oex, 980 m (1931–1994)
Montana, 1495 m (1931–1994)
Davos, 1590 m (1901–1994)
Säntis, 2500 m (1901–1994)

Figure 1 shows the locations of these six stations in Switzerland. The data were analysed for every season, on the basis of the following six climatological parameters:

Seasonal average daily minimum temperature (1901–1994); in tables, abbreviated as "Tmin"

Table 1. *Pearson's Correlation Coefficients for the Summer Season (for exact definitions of parameters, see text). Significant Coefficients According to Fisher's Test and to the Critical Values of Pearson's Product Moment Correlation Coefficient (Significance Level 0.01 or 99%) are Underlined*

	Tmin	Tmax	Prec. sum	Prec. days	Snowfall
Neuchâtel (487 m)					
Tmax	0.6144				
Prec. sum	−0.268	−0.5727			
Prec. days	−0.428	−0.7568	0.7886		
Zurich (569 m)					
Tmax	0.578				
Prec. sum	−0.2492	−0.5297			
Prec. days	−0.3874	−0.5765	0.7689		
Château-d'Oex (980 m)					
Tmax	0.4613				
Prec. sum	−0.125	−0.5460			
Prec. days	−0.1139	−0.5907	0.7739		
Montana (1495 m)					
Tmax	0.8737				
Prec. sum	−0.3433	−0.4183			
Prec. days	−0.3927	−0.5105	0.7189		
Davos (1590 m)					
Tmax	0.7003				
Prec. sum	−0.1414	−0.2427			
Prec. days	−0.1516	−0.4303	0.5271		
Säntis (2500 m)					
Tmax	0.8923				
Prec. sum	−0.4191	−0.3326			
Prec. days	−0.4566	−0.4723	0.6335		
Snowfall	−0.5354	−0.5481	0.5270	0.4609	
Snow depth	0.1979	−0.0102	−0.3995	−0.0443	−0.1081

Seasonal average daily maximum temperature (1901–1994); ("Tmax")
Seasonal 24-h precipitation sum (1901–1994); ("Prec. sum")
Seasonal average number of days with precipitation $\geqslant$ 1 mm (1901–1994); ("Prec. days")
Seasonal average snow depth (1931–1994); ("Snow depth")
Seasonal average 24-h snowfall (1931–1994); ("Snowfall")

Correlation coefficients between the different parameters were calculated and evaluated according to Fisher's T-test and to the critical values of Pearson's product moment correlation coefficient (significance level 0.01), mainly in order to allow a comparison between r-values obtained for different volumes of data.

3. Summer

In summer, correlation between temperature and precipitation is usually significant and always negative. This means that a cool summer is generally accompanied by important precipitation, and vice versa. The relationship between minimum temperature and precipitation parameters is not very significant, although it is often more so on the Swiss Plateau as well as on certain mountain tops (Säntis) or middle and upper slopes (Montana). It is not significant for sites located on valley floors (Davos and Château-d'Oex). In these locations, temperatures are not only low during rainy weather but also at night, when cold air pools and local breezes may occur. Concerning the precipitation parameters, the best correlation with temperature is always found with the number of days with precipitation (Figs. 2 and 3); the cooling due to weather with precipitation is not so much linked to the intensity of the precipitation event or to the quantity of rainfall as to the frequency and length of the precipitation period. The highest correlation coefficient is always found between maximum temperature and the number of days with precipitation.

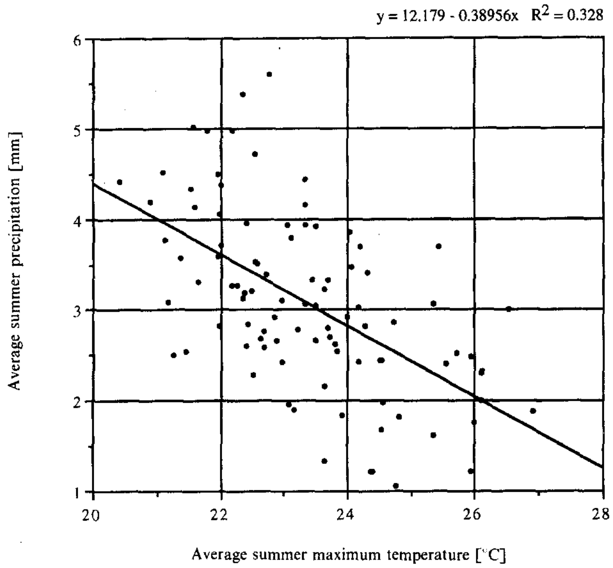

Fig. 2. Relationship between average summer maximum temperature and average summer precipitation amount in Neuchâtel (1901–1994)

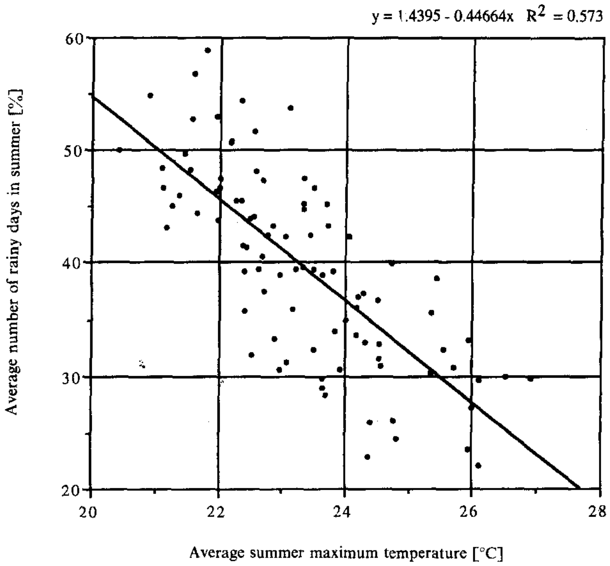

Fig. 3. Relationship between average summer maximum temperature and average number of days with precipitation in Neuchâtel (1901–1994)

Snow data in summer only make sense for high elevations (Säntis). The correlation with temperature shows that there is a distinct relationship with the amount of snowfall and no relationship with the seasonal average snow depth. The amount of snowfall is better correlated with temperature than with precipitation. This means that colder summers are associated with more snowfall; average snow depth, however, depends on a more complex relationship between meteorological parameters, where not only temperature and precipitation but also sunshine, surface energy balance and wind play interrelated roles.

4. Winter

Relationships between temperature, precipitation and snow are clearly more complex in winter than in summer, essentially because of the frequent presence of winter high pressure regimes over the Alps. These are accompanied by temperature distributions characterized by cold, stagnant air at low elevations, often located below a persistant stratus cover, and relatively mild air at higher elevations, where the diurnal cycle is generally of higher amplitude (Beniston et al., 1994, 1996). In absolute terms, day-time temperatures can sometimes even be higher in the mountains than below the stratus cover. Precipitation during such high-pressure situations is generally inexistant. The frequency and persistance of these episodes induces a distinct signal in the temperature and precipitation record, so that it is difficult to derive simple temperature/precipitation relationships.

The correlation coefficients given in Table 2 provide a good illustration of this mechanism.

Table. 2. *Pearson's Correlation Coefficients for the Winter Season (for Exact Definitions of Parameters, see text). Significant Coefficients According to Fisher's test and to the Critical Values of Pearson's Product Moment Correlation Coefficient (Significance Level 0.01 or 99% are Underlined*

	Tmin	Tmax	Prec. sum	Prec. days	Snowfall
Neuchâtel (487 m)					
Tmax	0.9415				
Prec. sum	0.2324	0.2747			
Prec. days	0.2655	0.2923	0.8452		
Snowfall	−0.5172	−0.5149	0.2929	0.2657	
Snow depth	−0.6155	−0.6008	0.1736	0.0914	0.8217
Zurich (569 m)					
Tmax	0.9111				
Prec. sum	0.2433	0.2868			
Prec. days	0.2459	0.2802	0.8107		
Snowfall	−0.5143	−0.5385	0.3149	0.3629	
Snow depth	−0.5994	−0.6213	0.1832	0.2043	0.8669
Château-d'Oex (980 m)					
Tmax	0.8929				
Prec. sum	0.2459	0.0702			
Prec. days	0.0681	−0.1988	0.7895		
Snowfall	−0.4892	−0.6388	0.411	0.6441	
Snow depth	−0.6600	−0.6911	0.1893	0.3894	0.8519
Montana (1495 m)					
Tmax	0.9296				
Prec. sum	−0.0328	−0.1950			
Prec. days	−0.1932	−0.3876	0.8325		
Snowfall	−0.3352	−0.4863	0.8286	0.8177	
Snow depth	−0.3886	−0.4889	0.7457	0.7303	0.8703
Davos (1590 m)					
Tmax	0.9432				
Prec. sum	0.1103	0.0445			
Prec. days	−0.0043	−0.1508	0.6089		
Snowfall	0.0293	−0.0673	0.9384	0.6661	
Snow depth	−0.1409	−0.2016	0.5667	0.4192	0.6869
Säntis (2500 m)					
Tmax	0.9563				
Prec. sum	0.0626	0.0782			
Prec. days	−0.4370	−0.4149	0.6105		
Snow fall	−0.5626	−0.5259	0.4856	0.7315	
Snow depth	−0.2105	−0.1660	0.2955	0.4074	0.2499

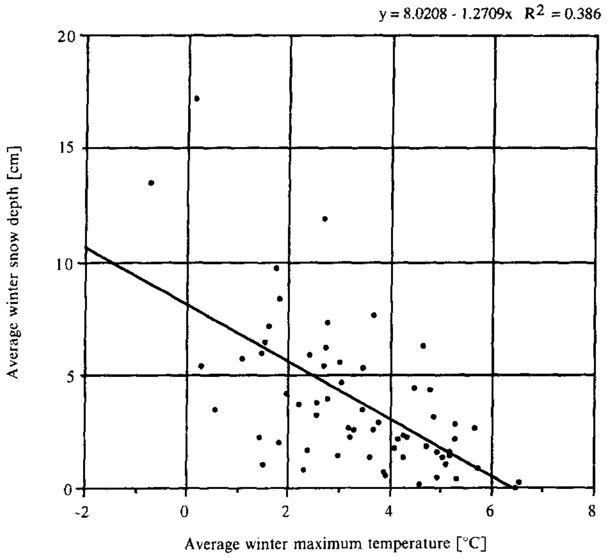

Fig. 4. Relationship between average winter maximum temperature and average winter snow depth in Zurich (1931–1994)

On the Swiss Plateau, the relationships between temperature and snow parameters are high and negative, whereas they are low but always positive between precipitation and snow. At higher altitudes, the link between temperature and snow is weaker though still mostly negative, but sometimes not significant, while the relationship between precipitation and snow is more significant than on the Plateau.

This means that in winter, at lower altitude sites up to 1000–1500 m above sea level, the amounts of snowfall and snow depth tend to increase with lower temperatures, and vice-versa (Fig. 4); the link between snow parameters and precipitation frequency and amount is rather weak, although there is a tendency for both to jointly increase or decrease. Above the 1000–1500 m range, the amounts of snowfall and snow depth are more closely linked to precipitation than to temperature; in some instances the link with temperature can even be inexistant. This phenomenon is particularly obvious in the valley location of Davos, whereas at Säntis as well as in Montana, the correlation between snowfall and temperature is negative and significant. The reason for explicitely focusing on this elevation range is that this is where many of the Alpine sports resorts are located; this medium altitude range would be particularly sensitive to climate change and snow amount, impacting heavily on the tourist industry in the mountains, according to preliminary reports of the IPCC (Beniston et al., 1995a); the 1000–1500 m altitude range was already considerably affected during the sequence of warm, snow-free winters which occured at the end of the 1980s in the Swiss, French, and Austrian Alps.

Contrary to what was previously discussed concerning summer data, the relationship between temperature and precipitation is positive in winter on the Swiss Plateau. This link tends to weaken in the mountains, apart from some significant negative correlations between temperature and precipitation frequency in Säntis and Montana.

5. Conclusions

The analysis of correlation coefficients between temperature, precipitation and snow has shown that there is a high *negative* relationship between summer temperature and precipitation. Cold summers tend to be associated with more precipitation, mainly in terms of its frequency of occurence, but also in terms of its abundancy. Maximum temperature values exhibit stronger relationships with precipitation data than do minimum temperatures.

In winter, for lower altitude sites, on the contrary (and contrary to what was shown for the climate of the Middle East by Striem, 1974), there is a low positive correlation between temperature and precipitation. However, there is a high negative correlation between temperature and snow. This means that for lower altitudes, warmer winters tend to be rainier and are associated with less snow; the fact that only a small part of winter precipitation falls in the form of snow explains this apparent paradox.

In the mountains above 1000–1500 m, the link is strongest between snow and precipitation while correlations are mostly low between temperature on the one hand and precipitation or snow on the other. Whenever there is a significative correlation between temperature and one of the other parameters studied, it is negative; this implies that in the mountains, warmer winters tend to be linked to less snow and less precipitation.

These results can be used on two levels, firstly as a tool to better understand past climate and past events linked to climate modifications (Ornato, 1988; Neumann, 1993), and secondly to make some inferences about potential future climate change. It has been shown that there is indeed a significant correlation between summer precipitation and temperature, which reinforces Neumann's conclusions about the climatic conditions in Europe during the cold phase between 1700 BC – 1470 BC as well as during the Löbben Phase (1400 BC – 1230 BC) which resulted in population migrations. These periods were put into evidence mainly from glaciological studies, where it has been demonstrated that there was an advance of glaciers at that time; this is only partly confirmed by tree-ring analysis, pollen analysis and analysis of lake levels (Röthlisberger, 1986). The results discussed in this paper support the hypothesis that the cold summers during these periods were probably linked to frequent and abundant precipitation. In human terms, the occurence of precipitation (especially frequent precipitation) associated with low summer temperatures led to difficult conditions for agriculture in Europe (crop failure, floods, pests, and disease), which in turn resulted in increased mortality as well as population migrations (Pfister, 1988; Rebetez, 1994, 1995).

In terms of potential future global warming, the expected higher summer temperatures will likely be linked to a decrease of precipitation, while higher winter temperatures will probably be associated to an increase of precipitation but a decrease of snow on the Swiss Plateau, and a decrease of precipitation and snow in the mountains. All these conditions combine to accelerate the retreat of the glaciers in the Alps in a generally warming climate (Maisch, 1992; Haeberli, 1994), contrary to what is expected to take place in boreal regions (Bryson, 1994), where milder winters are expected to produce more snowfall and thereby increase the volume of continental glaciers.

The apparent paradox of warmer summers and reduced precipitation (when globally, higher temperatures are almost certain to be accompanied by higher precipitation) is explained by substantial differences in climate response on the regional scale; this is to be expected particularly in a region as topographically complex and as climatologically diverse as the Alps. Indeed, recent high-resolution climate modeling experiments, focusing on the Alpine domain, using a nested general circulation model/limited area model (GCM/LAM) approach, tend to confirm the conclusions mentioned in this paper on the basis of observational evidence. The GCM/LAM simulations of future climate, under enhanced atmospheric greenhouse-gas concentrations, indicate that while temperatures will be warmer in both winter and summer in the Alps, winter precipitation is projected to increase, while summer precipitation is projected to decrease (Beniston et al., 1995b).

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Author's address: Dr. Martine Rebetez, Department of Geography of the Universities of Lausanne and Fribourg, IGUF – Pérolles, CH-1700 Fribourg, Switzerland.