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Frequency Changes of Weather Types in the Alpine Region since 1945

G. Stefanicki, P. Talkner, and **R. O. Weber**

Summary

The annual occurrence of different weather types of Schüepp's synoptic classification in the Alpine region has significantly changed since the beginning of its recording in 1945. The annual frequency (number of days per year) has shifted towards more convective and less advective weather types. Since 1945 the number of long-lasting convective episodes rose and the number of long-lasting advective episodes lessened. Most of these changes took place in winter. The annual frequencies of weather types and the annual mean of certain local meteorological parameters are significantly correlated. On the large scale there is a strong interdependence between the high pressure weather type and the North Atlantic Oscillation (NAO) index which is based on the sea-level pressure difference between Portugal and Iceland.

1. Introduction

The likely existence of a global climate change has become widely accepted in recent years. According to the latest IPCC report (Houghton et al., 1996) the annual global mean temperature of earth's surface has increased by about 0.3 to 0.6 K since the late 19th century. The observed warming has not been globally uniform, as some areas even have cooled. Many publications have recently investigated regional aspects of climate changes in Europe. Some of them are discussed below. Variations of temperature, precipitation and sunshine duration have been examined on a regional and local scale. Further, large-scale pressure distributions over Europe and the eastern Atlantic have been analysed.

Schönwiese et al. (1994) investigated seasonal temperature and precipitation trends in Europe from 1891–1990. An increase of temperature was noticed in North-Eastern Europe during spring by more than 2 K/100 years and in Eastern Europe during winter by even more than 2.5 K/100 years. Weber et al. (1997) compared extreme and mean daily temperatures from 29 low altitude and mountain stations of 7 countries in Central Europe. The analysis shows spatial patterns of similar changes in maximum and minimum daily temperatures and diurnal temperature range. Weber et al. (1994) studied the height dependence of temperature changes in the Alpine region. Most notably, on mountain stations both the minimum and maximum temperature show an increase, whereas at low altitude stations only the minimum temperature has significantly increased. Beniston et al. (1994) analysed a number of climatological parameters in Switzerland from 1901–1992 showing that the observed climate trends in Switzerland are consistent with global warming tendencies. The rate of warming is even enhanced as compared to the global development. Balling (1995) investigated the variations in temperature and precipitation in Germany in the last 140 years. The annual mean temperature has increased whereby the main warming took place in the cooler periods of the year. The German precipitation data (Balling, 1995) do not show a significant trend. Weber (1990) analysed the sunshine duration of 54 stations in Germany during the period 1951–1987. Sunshine generally decreased over the central part of the country and in the central German hills, and shows no apparent correlation with the changes of other parameters. The decline of sunshine is attributed to changes in large-scale features of the general atmospheric circulation over the North Atlantic and Europe (Weber, 1990). An analysis of cloud data from Berlin-Dahlem (1955–1993) indicates that an increase of cloudiness is linked to a decrease of the temperature range (Weber, 1994). Auer and Böhm (1994) studied the temperature and precipitation data in Austria of the last 150 years. In the western part of Austria warm and wet climate has increased whereas in the eastern part warm and dry conditions have become more frequent. Dobesch (1992) examined the sunshine duration in Austria in the years 1960–1989 and found a decrease in northern and eastern parts of Austria, whereas in the high mountain regions sunshine duration has increased.

Kożuchowski (1993) defined an index of zonal circulation between 35° N and 65° N and analysed its variations during the period 1899–1990. An increase of the zonal index occurred during the 1970 s and 1980 s and is in general associated with an increase of air temperature in Europe. Lamb (1988) described in his book the changes in frequency of prevailing winds over the British Isles and the North Sea region. He noticed a tendency to parallelism between the changes of prevalence of the westerlies and the general temperature level in England and Europe. Since 1950 an increase in precipitation in the east and northeast of the British Isles is reported. Hess and Brezowsky (1952, 1977) defined a classification of large-scale weather types (Grosswetterlage) for Europe and the eastern Atlantic. For this classification the atmospheric circulation of several days is taken into account. Klaus and Stein (1978) analysed the 'European Grosswetterlagen' for the period 1881–1973. Decreasing annual frequencies of the so-called half-meridional circulation pattern and corresponding increasing annual frequencies of the meridional circulation pattern are registered since the middle of this century. For many atmospheric circulation types, as classified by the scheme of Hess and Brezowsky, Bárdossy and Caspary (1990) reported changes of both the annual and the seasonal frequencies since 1881. The frequency of zonal circulation has increased in December and January since about 1973 and that of cold meridional circulation has decreased in September and December. Accordingly mild and humid winters in Central Europe have become more frequent since the beginning of the seventies.

Fraedrich and Müller (1992) found that climate anomalies in Europe are associated with ENSO (El Niño-Southern oscillation) warm and cold extremes. ENSO is the term for the coupled ocean-atmosphere interactions in the tropical Pacific characterized by episodes of anomalously high sea surface temperatures in the equatorial and tropical eastern Pacific, associated with large-scale swings in surface air pressure between the western and eastern tropical Pacific. Negative pressure anomalies at western and central European stations are associated with positive temperature and precipitation anomalies during warm-winter ENSO events. The reversed signal is observed over Northern Europe. During cold ENSO episodes the region of negative pressure anomalies is shifted northward and higher pressure anomalies are observed over Central Europe.

Hurrell (1995) discovered that the North Atlantic Oscillation index (NAO) has exhibited an upward trend over the past 25 years with unprecedented large positive values. The NAO index describes the pressure distribution over the northern Atlantic. Winters with a high NAO index relate with dry conditions over southern Europe and unusually wet conditions over northern Europe. The westerlies with their moderating influence of the ocean extend much farther northward over Europe and Scandinavia when the NAO index is high (Hurrell, 1995). In a recent publication, Wanner et al. (1997) present an overview of large scale climatic variability and the Alpine climate.

For our investigation a restricted area – the central part of the Alps – is considered. This region is a transition zone between the Atlantic weather regime, a continental regime and the regime of the Mediterranean Sea. We have studied whether the observed global climate change has an effect on the weather conditions in this region and to which extend a possible change of weather is related to both, large-scale and local meteorological parameters. As a regional parameter we analysed Schüepp's synoptic weather types, their possible relations to local meteorological parameters and also to the large-scale NAO index and to solar parameters.

In section 2 the definition of Schüepp's weather classification is presented. The frequencies of the weather types are discussed in section 3 and their relation to meteorological parameters is analysed in section 4. Section 5 treats possible links of weather type frequencies with large-scale meteorological quantities.

2. Schüepp's Synoptic Classification

Before the development of numerical weather predictions most weather forecasts were based on empirical knowledge. Still today, the interpretation of the numerical predictions relies on empirical knowledge. In 1957 Schüepp suggested a classification scheme of weather types for Switzerland. In contrast to the 'Grosswetterlagen' of Hess and Brezowsky (1977) Schüepp's (1979) modified classification of a synoptic weather type only takes into account the meteorological conditions of the considered day. Salvisberg (1996) compared different classification schemes, among them the Hess-Brezowsky classification and Schüepp's classification of weather types. She showed that there is no apparent direct relation between these two schemes. Almost each Schüepp weather type can occur during any given Hess-Brezowsky 'Grosswetterlage' and vice versa.

In Schüepp's classification scheme a region of 444 km in diameter in the central part of the Alps is considered. The relevant parameters for determining a synoptic weather type are the distribution of surface pressure, the geostrophic wind direction which follows from the surface pressure distribution, the upper-level wind speed and direction and the height of the 500 hPa surface, for further details see Appendix. Schüepp's weather types are determined on the basis of observed data by strict rules (see Appendix). The classification criteria are manually determined from weather maps, therefore the classification is called semi-objective (Wanner et al., 1997). The synoptic weather types have been classified by the SMA back to January 1st 1945.

Based on these specific criteria three main classes have been defined: the convective, the advective and the mixed weather type. The convective weather type consists of the three subclasses of high, flat and low 500 hPa pressure distribution, corresponding to anticyclonic, indifferent and cyclonic situations. The advective weather type consists of the four subclasses of westerly, northerly, southerly and easterly winds (at 500 hPa). Mean pressure maps for the three main and the seven subclasses are shown in the Appendix (Fig. 9). The seven subclasses together with the mixed weather type can further be divided into a total of 40 groups. However, the latter detailed classification will not be considered here.

3. Annual and Seasonal Frequencies of the Weather Types

The annual occurrence of the three main weather types was calculated for each year of the observation period 1945–1994 and is shown in Fig. 1. The occurrence of the mixed class is roughly an order of magnitude smaller than that of the other two classes and has a slight decrease since 1945. The annual frequency of the

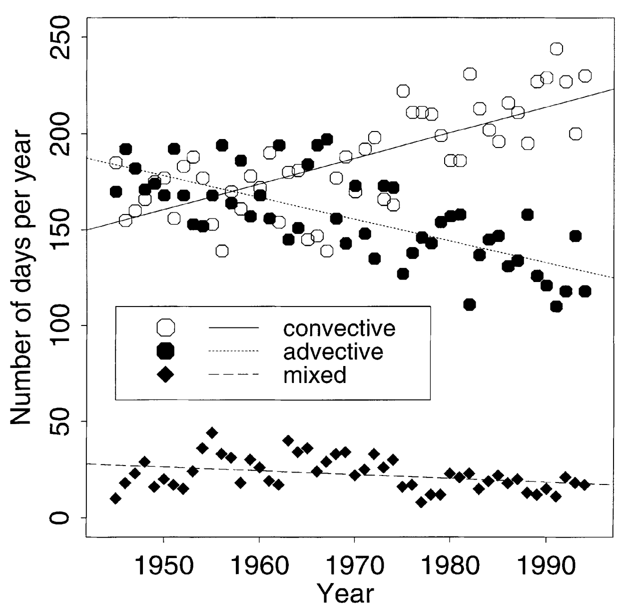

Fig. 1. Annual occurrence of convective, advective and mixed weather types and linear regression lines (data 1945–1994)

advective weather type has decreased strongly whereas the number of days per year of the convective weather type has increased correspondingly. A linear trend analysis exhibits an increase of the convective weather type of 13 days per 10 years and a decrease of the advective weather type of 11 days per 10 years. Both linear trends are significant at the 0.1% level according to a standard t-test (Draper and Smith, 1981), see Table 1.

Table 1. *Mean Occurrence (Days per Year) and Linear Trend (Days per 10 Years) of the Main Classes and Subclasses of Schüepp's Weather Types for the Period 1945–1994. Trend Values in Bold are Significant at the 0.1% Level, in Normal the 1% Level and in Italics not at the 1% Level*

Weather type	Mean annual occurrence	Trend
Main classes:		
Convective	187	**13.3**
Advective	156	**−11.3**
Mixed	22	*−1.9*
Convective:		
High	60	**9.1**
Flat	100	3.8
Low	27	*0.4*
Advective:		
Westerly	40	−2.7
Northerly	61	**−5.3**
Easterly	19	−2.1
Southerly	36	*−1.3*

Although there is evidence for inhomogeneities in the weather type classification in the mid-seventies (Wanner et al., 1998 and references therein; Salvisberg, 1996), Fig. 1 does not show a discontinuity around 1975 as would be expected for a sudden change in the data used for the classification. A trend analysis of the weather type frequencies from 1975 to 1994 (see also Table 3 of Wanner et al., 1997) gives the same qualitative behavior as the trend analysis over the whole period 1945–1994 (Table 1).

An analysis of the annual occurrence of each subclass shows further details. The frequency increase of convective weather type is mainly due to an increase of the occurrence of the high pressure weather type, see Table 1 and Fig. 2a. The number of low pressure weather types has remained practically unchanged. Among the advective weather type the northerlies have the largest decrease in frequency (see Table 1 and Fig. 2b), followed by the westerlies.

To see how the changes are distributed over the year the data set was divided into four seasons. A linear trend analysis makes it evident (see Table 2) that winter (December, January and February) has the largest increase for the convective class, followed by autumn (September, October and November). Most of this increase is due to the increase of high pressure weather type, both in winter and in autumn. The

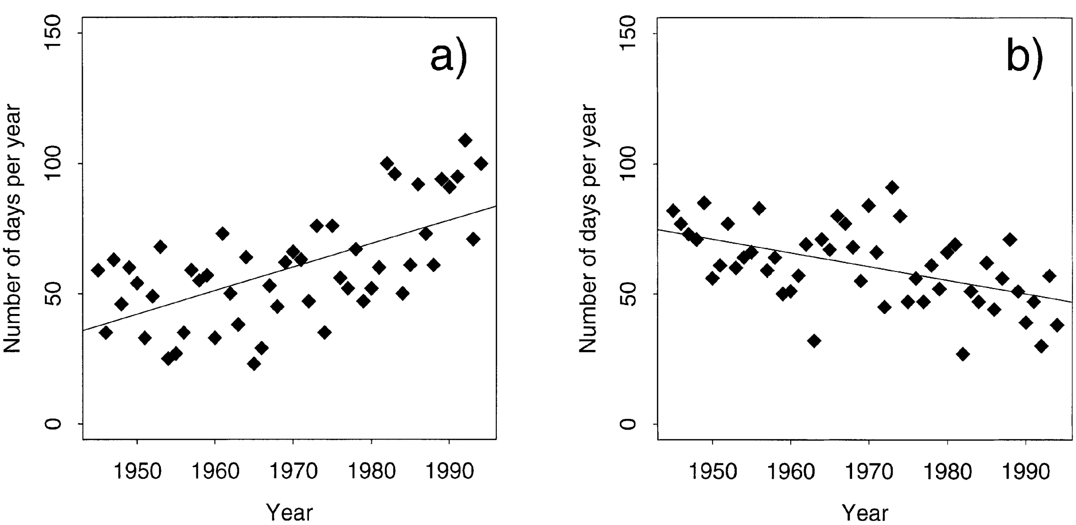

Fig. 2. Annual occurrence of a) high pressure weather type (subclass with largest frequency increase) and b) northerly weather type (subclass with largest frequency decrease) and linear regression lines (data 1945–1994)

Table 2. *Linear Trend (Days per 10 Years) of Schüepp's Weather Types during the Four Seasons. The Values in Bold are Significant at the 0.1% Level, in Normal at the 1% Level and in Italics not at the 1% Level. Winter is Taken as December, January and February, Spring as March, April and May, Summer as June, July and August and Autumn as September, October and November*

	Winter	Spring	Summer	Autumn
Convective	**5.5**	2.3	**2.6**	**3.1**
Advective	−**4.6**	−2.1	−2.1	−**2.6**
Mixed	−0.9	*−0.2*	*−0.5*	*−0.5*
High	**3.9**	*0.8*	2.3	*2.0*
Flat	1.8	*0.4*	*0.8*	*0.9*
Low	*−0.2*	*1.1*	*−0.5*	*0.1*
Westerly	*−0.4*	*−0.9*	*−1.0*	*−0.5*
Northerly	−**2.2**	*−0.8*	*−0.9*	*−1.3*
Easterly	*−0.8*	*−0.5*	*0.0*	*−0.7*
Southerly	−1.2	*0.1*	*−0.2*	*−0.2*

advective class shows the largest decrease in winter and autumn, confirming that an increase of convective weather type corresponds to a decrease of advective weather type.

In order to describe this opposite development of the frequencies of convective and advective weather types in more detail we investigated the persistence of these weather types. For this purpose we introduce an *episode* as an uninterrupted sequence of days with the same weather type.

Since the frequency of the mixed weather type has approximately remained unchanged only the convective and advective weather types were analysed. Among all data the longest observed single episode is convective. It began on 6 August 1976 and lasted 34 days. The longest advective episode began on 12 November 1965 and lasted 25 days. We split the whole data set into an earlier period from 1945 till 1969 and a later one from 1970 till 1994 and calculated the average episode length of the two considered periods. Between the first and the second period the average length of convective episodes rose by 19% from 2.71 to 3.35 and that of advective episodes fell by 15% from 2.65 to 2.30. However, the mean total number of episodes per year of the convective and advective weather types remained with about 62 episodes practically unchanged. Thus, the frequency change of the weather types is caused by a change of the length of the episodes, with a tendency towards longer convective episodes and shorter advective episodes, and not by a change of the number of episodes per year.

Further, we compared the distributions of the episode lengths within the considered time periods for each of the two weather classes. For each episode length the differences of the respective frequencies in the periods 1970–1994 and 1945–1969 are shown in Fig. 3a. While the differences of the one-day-episodes almost

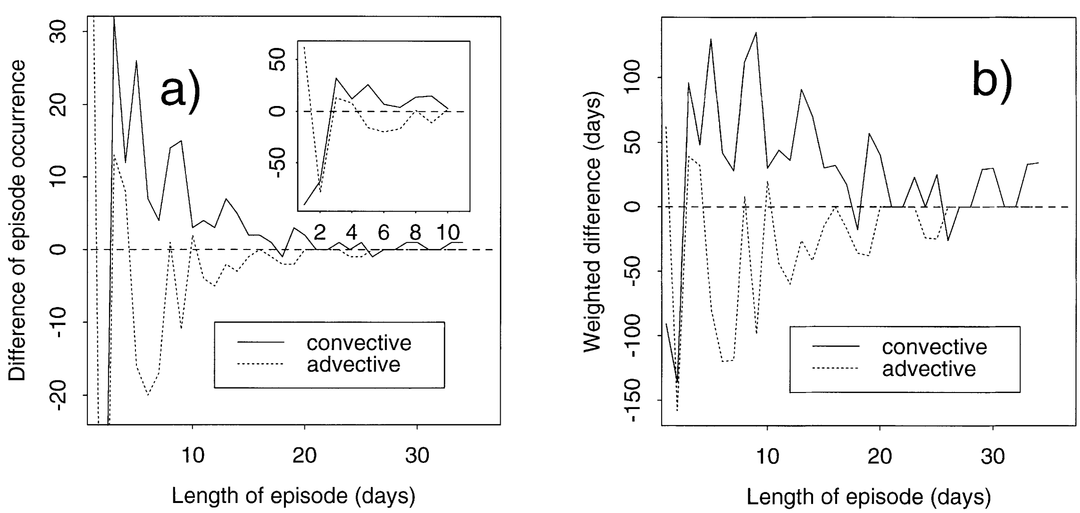

Fig. 3. Frequency changes of convective and advective episodes as a function of episode length. Difference between total occurrences of episodes in the periods 1970–1994 and 1945–1969 is shown in a) as absolute counts, the inset shows short episodes lengths; in b) as counts weighted by the episode length

compensate each other, two-day-episodes of both weather types occurred less frequently in the second than in the first period, whereas three and four-day-episodes have become more frequent. Longer convective episodes have been more frequent after 1970 while most of the longer advective episodes show a decreasing tendency.

In order to identify those episode lengths of each class that have the largest influence on the frequency change of convective and advective types in the two time periods, we multiply the differences of the respective episode frequencies by their duration. These weighted differences are shown in Fig. 3b. It reveals that the largest increase of the number of the convective weather types is caused by episodes in the range of 3 days to 15 days. Roughly within the same range the number of the advective weather types has decreased.

4. Relation to Local Meteorological Parameters

To investigate a possible link between the occurrence of weather types and meteorological parameters and their respective changes, we examined the correlation of the annual frequency of weather types with annual means of several local meteorological parameters. The chosen parameters are: daily mean temperature (T-mean), daily minimum temperature (T-min), daily maximum temperature (T-max), daily mean pressure (P-mean) and daily cloudiness (cloud). Temperature and pressure have been obtained by measurements, cloudiness has been estimated by observers.

Basel-Binningen, Zürich SMA and Neuenburg as low altitude stations and Säntis, the Zugspitze in Germany and the Sonnblick in Austria as stations situated on mountain tops have been selected (see Table 3). All stations have records back to the beginning of this century at least. The low altitude stations are representative for the area north of the Alps for which the weather types are defined. Data from further low altitude stations are available but for the present purpose their consideration does not provide further understanding. For the Zugspitze in some months

Table 3. *List of Stations Used in this Study*

Station	Location	Elevation (m)
Basel-Binningen	47°33′N, 7°35′E	316
Zürich SMA	47°23′N, 8°34′E	556
Neuenburg	47°00′N, 6°57′E	485
Säntis	47°15′N, 9°21′E	2490
Zugspitze	47°25′N, 10°59′E	2960
Sonnblick	47°03′N, 12°57′E	3105

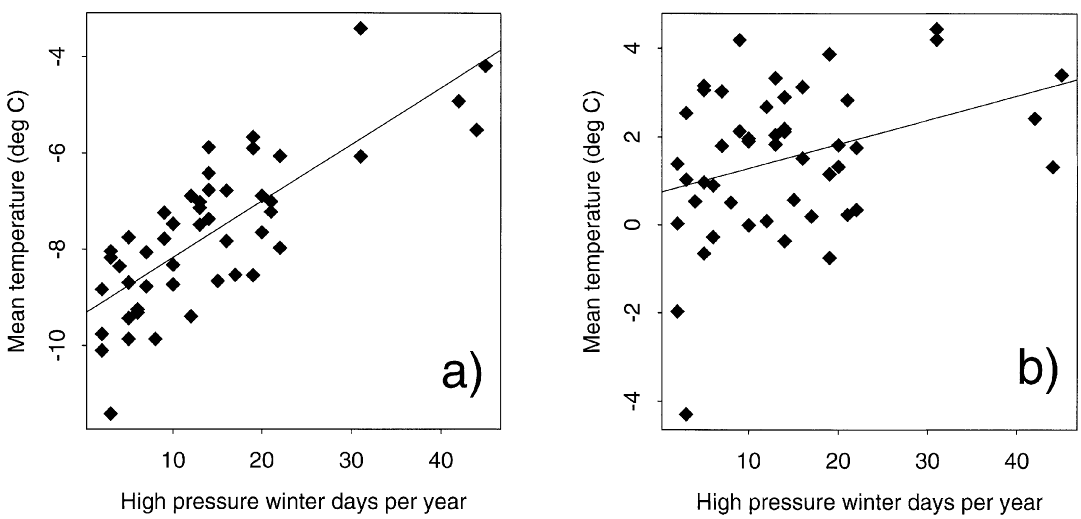

Fig. 4. Winter mean (December, January and February) of daily mean temperature versus number of winter days with high pressure weather type **a**) Säntis with a correlation coefficient of 0.78 and **b**) Basel-Binningen with a correlation coefficient of 0.34. The temperature $-4.3\,°C$ in Basel dates from 1963, a very cold winter, when for the last time most of the lakes in Switzerland were covered by ice (SMA, 1964)

in 1945 all values are missing. Data from the other stations are complete. The data have been checked for inhomogeneities by comparing the values of pairs of stations as described in Weber et al. (1994) and have been homogenized if necessary.

We investigated a possible interdependence between the occurrence of the weather types with the mentioned meteorological parameters. For this purpose the annual or seasonal mean of a certain parameter is plotted versus the corresponding number of days with a certain weather type. Figure 4a and 4b present two examples: the winter mean (December, January and February) of daily mean temperature versus the corresponding number of days with high pressure weather type for the two stations Säntis and Basel-Binningen. There is an evident interdependence which can well be described by a linear relationship between these two parameters. Pearson's correlation coefficient for a linear interdependence is found to be 0.78 for the Säntis (Fig. 4a) and 0.34 for Basel-Binningen (Fig. 4b). The value for Säntis is significant at the 0.1% level and for Basel-Binningen it is not significant at the 1% level.

The correlation coefficients of the annual occurrence of the weather types with the above mentioned meteorological parameters are listed in Tables 4 and 5 for the two stations Säntis and Basel-Binningen representing the mountain and low altitude stations, respectively. At the mountain station Säntis (Table 4, Fig. 4a) the convective weather type, in particular the high pressure events, show pronounced correlations with most of these parameters. Very high absolute values have been found for the correlation between the high pressure weather type and the annual mean station pressure. This fact reflects a strong correlation between the 500 hPa height and the surface pressure distribution. The correlations of the high pressure weather type with the annual mean temperature and the annual mean of the minimum and maximum temperature are also significant. The increase of the annual mean of the minimum and maximum temperature as reported by Weber et al. (1994) and the increase of the annual mean pressure (Beniston et al., 1994) correspond to an increase of the number of high pressure events and is confirmed by the high positive correlation coefficients.

Table 4 shows that the low pressure and the westerly weather types have significant negative correlations with the temperature and pressure and significant positive correlations with the cloudiness at the mountain station Säntis. These two weather types are known as types which bring 'bad' weather and the correlation values support their 'bad' reputation. In general, the absolute values of the correlations of weather types with the cloudiness are low, although one might expect a significant negative correlation

Table 4. *Correlation Coefficients Between the Annual Occurrence of Weather Types and Several Meteorological Parameters on Säntis. The Values in Bold are Significant at the 0.1% Level, in Normal at the 1% Level and in Italics not at the 1% Level. (T-mean = daily mean temperature, T-min = daily minimum temperature, T-max = daily maximum temperature, P-mean = daily mean pressure, Cloud = daily cloudiness)*

	T-mean	T-min	T-max	P-mean	Cloud
Convective	**0.53**	**0.58**	**0.45**	**0.51**	*−0.03*
Advective	**−0.47**	**−0.52**	−0.40	−0.45	*−0.03*
Mixed	−0.37	−0.38	*−0.33*	*−0.36*	*−0.14*
High	**0.69**	**0.69**	**0.64**	**0.75**	*−0.24*
Flat	*0.29*	*0.33*	*0.23*	*0.17*	*0.05*
Low	**−0.51**	−0.44	**−0.54**	**−0.55**	0.39
Westerly	**−0.45**	**−0.47**	−0.44	**−0.56**	0.42
Northerly	−0.43	−0.44	−0.37	*−0.23*	*0.06*
Easterly	*0.04*	*−0.01*	*0.06*	*0.07*	−0.38
Southerly	*−0.04*	*−0.08*	*0.02*	*−0.23*	*−0.04*

Table 5. *Correlation Coefficients Between the Annual Occurrence of Weather Types and Several Meteorological Parameters in Basel-Binningen. The Values in Bold are Significant at the 0.1% Level, in Normal at the 1% Level and in Italics not at the 1% Level. (T-mean = daily mean temperature, T-min = daily minimum temperature, T-max = daily maximum temperature, P-mean = daily mean pressure, Cloud = daily cloudiness)*

	T-mean	T-min	T-max	P-mean	Cloud
Convective	**0.47**	**0.53**	*0.10*	*0.35*	*−0.13*
Advective	−0.37	−0.43	*−0.03*	*−0.31*	*0.13*
Mixed	**−0.47**	**−0.49**	*−0.26*	*−0.24*	*0.11*
High	**0.57**	**0.55**	*0.29*	**0.63**	*−0.32*
Flat	*0.23*	*0.28*	*0.04*	*0.03*	*−0.03*
Low	*−0.32*	*−0.16*	−0.44	**−0.51**	*0.32*
Westerly	*−0.19*	*−0.20*	*−0.03*	**−0.51**	*0.32*
Northerly	*−0.25*	*−0.30*	*−0.01*	*−0.03*	*−0.00*
Easterly	*−0.27*	*−0.35*	*0.04*	*0.15*	*−0.27*
Southerly	*−0.13*	*−0.13*	*−0.06*	*−0.32*	*0.17*

between the high pressure weather type and cloudiness. A reason for the observed weak correlation might be that a precise estimate of cloudiness is often difficult.

We have used the observed high correlation between high pressure weather type and local high pressure at Säntis in order to test the homogeneity of the time series of high pressure weather type. Local pressure at Säntis itself is without apparent inhomogeneities. Figure 5 shows the annual mean station pressure for the days with high pressure weather type. For the years 1945 till 1994 this conditional mean shows a statistic variability but no apparent systematic changes that would indicate an inhomogeneity of the high pressure weather type time series.

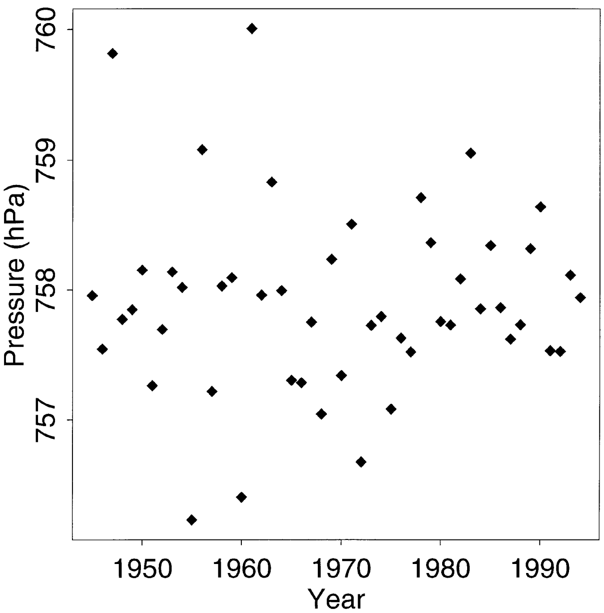

Fig. 5. Annual mean pressure on Säntis for those days with high pressure weather type since 1945. Data statistically scatter around a constant mean without systematic changes

The results for the low altitude stations, as shown in Table 5 for Basel, are similar as for the mountain stations but the absolute values of the correlation coefficients are in general smaller than those of the mountain stations. Some of the correlations which are significant at the 1% level for the mountain stations, are not significant at this level for the low altitude stations. Table 6 lists some selected correlation values for the low altitude and the mountain stations. It demonstrates that in general the influence of a weather type on certain parameters like minimum and maximum temperature is stronger at high elevations than at low altitude stations though the differences between these two groups are mostly not significant. The observed systematic tendency, especially the correlations of the high pressure weather type with T-min and T-max and of westerlies with T-min, might still indicate a more direct influence of the synoptic weather types on the meteorological parameters at mountain stations, whereas, at low altitude sites, a possible direct influence might be masked by more pronounced boundary layer effects.

The seasonal correlations are presented in Table 7. At mountain stations correlations between the high pressure weather type and the minimum and maximum temperature and the pressure are very high in winter and summer. As the annual frequencies of the high pressure weather type have increased, these high correla-

Table 6. *Selected Correlation Coefficients for the Stations Specified in Table 3. High and Low Pressure and the Westerly Weather Types were Correlated with Three Meteorological Parameters. The First Column Shows the Pairs of Variables that were Correlated. The Values in Bold are Significant at the 0.1% Level, in Normal at the 1% Level and in Italics not at the 1% Level. For Sonnblick and Zugspitze Data are from the Period 1945–1992*

	Säntis	Sonnblick	Zugspitze	Basel	Zürich	Neuenburg
High/T-min	**0.69**	**0.65**	**0.60**	**0.55**	**0.55**	**0.69**
High/T-max	**0.64**	**0.73**	**0.65**	*0.29*	*0.35*	**0.46**
High/pressure	**0.75**	**0.72**	**0.65**	**0.63**	**0.74**	**0.67**
Low/T-min	−0.44	−0.38	−0.45	*−0.16*	*−0.23*	*−0.22*
Low/T-max	**−0.54**	**−0.46**	**−0.51**	−0.44	**−0.50**	−0.37
Low/pressure	**−0.54**	**−0.55**	**−0.47**	**−0.51**	**−0.52**	**−0.52**
Westerly/T-min	**−0.47**	**−0.51**	**−0.47**	*−0.20*	*−0.26*	*−0.31*
Westerly/T-max	−0.44	−0.44	**−0.49**	*−0.02*	*0.05*	*−0.08*
Westerly/pressure	**−0.56**	**−0.55**	**−0.54**	**−0.51**	**−0.57**	**−0.51**

Table 7. *Selected Seasonal Correlation Coefficients for the Mountain and Low Altitude Stations. The High and Low Pressure Weather Types were Correlated with Three Meteorological Parameters. The First Column Shows Pairs of Correlated Variables. The Range of the Selected Correlation Coefficients for the Corresponding Stations are Given. The Values in Bold are Significant at the 0.1% Level, in Normal at the 1% Level and in Italics not at the 1% Level. For Sonnblick and Zugspitze Data are from the Period 1945–1992*

	Winter	Spring	Summer	Autumn
Mountain stations:				
high/T-min	**0.65/0.76**	0.44/**0.50**	**0.64/0.78**	**0.51/0.57**
high/T-max	**0.70/0.80**	0.44/**0.55**	**0.67/0.71**	**0.53/0.62**
high/pressure	**0.84/0.86**	**0.63/0.71**	**0.65/0.82**	**0.73/0.79**
low/T-min	−0.44/−**0.52**	*−0.26*/−0.41	−0.41/−**0.49**	−0.39/−**0.45**
low/T-max	**−0.53/−0.56**	*−0.31*/−**0.48**	−0.46/−**0.60**	**−0.47/−0.52**
low/pressure	**−0.60/−0.62**	**−0.52/−0.64**	**−0.55/−0.70**	**−0.63/−0.69**
Low altitude stations:				
high/T-min	*0.30*/0.40	*0.44*/**0.54**	**0.69/0.79**	*0.16/0.30*
high/T-max	*0.33/0.34*	**0.53/0.55**	**0.66/0.70**	*0.23/0.33*
high/pressure	**0.80/0.84**	**0.57/0.60**	0.37/**0.57**	**0.69/0.73**
low/T-min	*−0.36*/−0.40	*−0.19/−0.30*	−0.37/−**0.49**	*−0.00/−0.09*
low/T-max	*−0.44/−0.46*	**−0.49/−0.57**	**−0.47/−0.55**	*−0.27/−0.30*
low/pressure	**−0.50/−0.53**	**−0.54/−0.55**	**−0.53/−0.63**	**−0.64/−0.64**

tions confirm the increase of the minimum and maximum temperature at high elevations reported by Weber et al. (1994). At low altitude stations the correlations of high pressure weather type with minimum and maximum temperature is weak in autumn and winter. This might be caused by the frequent occurrence of high pressure inversion situations in autumn and winter, which are accompanied by a persistent cold air pool with fog at low altitude stations, while on mountain tops sun is shining. Under these conditions the weather at low altitude and on mountains is decoupled. Winter has the highest correlations between the high pressure weather type and the pressure, while in summer high pressure weather type and minimum and maximum temperature correlate best. The latter confirms the common feeling that high pressure goes with nice and warm weather. The seasonal correlations again confirm the observed tendency of a more direct influence of the weather types on the meteorological parameters at mountains stations. Finally, we note that at low altitude stations the easterlies in winter have a significant negative correlation with all three temperature parameters with values between −0.53 and −0.64 (not shown in Table 7). These weather types are known as ‘Bise-situations’, a cold east-northeast wind, described in Wanner and Furger (1990). This correlation is less pronounced on mountains in good agreement with the findings of Wanner and Furger (1990), who characterize the Bise as an air transport mainly through the lower regions of the Swiss Midland.

5. Relation with Global Indices

In order to test to which extent the occurrences of the synoptic weather types in the Central Alps are influenced by large scale meteorological conditions and fluctuations of energetic forcing of the atmosphere, we used two large-scale parameters, namely the NAO index (Hurrell, 1995) and a sunspot index.

The NAO index characterizes the pressure distribution over the northern Atlantic. It is defined as the normalized sea-level pressure difference between Lisboa (Portugal; 38°26′ N 9°05′ W) and Stykkisholmur (Iceland; 65°03′ N 22° 26′W). Mean values of 4-months-winters (December until March) are given in Hurrell (1995). This winter NAO index shows an increase since 1945 that can be characterized by a linear trend of 2.6 per 50 years, significant at the 1% level [see Figure 1A of Hurrell (1995)]. Large positive NAO indices are linked to dry conditions over southern Europe and wetter than normal conditions over northern Europe (Hurrell,

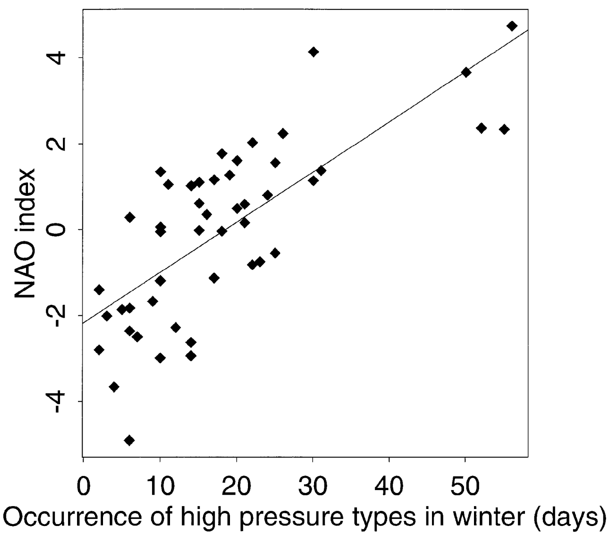

Fig. 6. The NAO index versus the occurrence (number of days per winter) of high pressure weather type of the 4-months-winter (December, January, February and March). The correlation coefficient is 0.74, significant at the 0.1% level

1995). Furthermore, Hurrell (1996) has shown that most of the observed warming across Europe and the simultaneous cooling in the northwest Atlantic since the seventies is strongly correlated with the changes of the NAO index. The Alps represent a natural border region between the southern and the central and northern regions in Europe. One therefore may ask whether there is a relation between the north-south pressure gradient over the Atlantic characterized by the NAO index and the occurrence of the weather types as defined for the central part of the Alps.

We calculated the correlation of the NAO index with the annual occurrence of the weather types which cover the same time-range (4-months-winter consisting of December, January, February and March). The occurrence of the high pressure weather type correlate well with the NAO index (see Fig. 6 and Table 8). This indicates that the pressure distribution over the North Atlantic influences the weather types of the Alpine region. Hurrell's (1995) findings of a northward shift of westerly winds over Europe agree with the increase of high pressure weather type over the Alps and the results of Hurrell and van Loon (1997), who found a positive correla-

Table 8. *Correlation Coefficients Between the NAO Index and the Occurrence of Weather Types. Correlations are Given for Winter (December, January, February and March). The Values of the 4 Subclasses of the Advective Weather Type are all Small and not Significant and therefore Omitted in the Table. The Values in Bold are Significant at the 0.1% Level, in Normal at the 1% Level and in Italics not at the 1% Level*

	Dec-Mar
Convective	**0.50**
Advective	−0.41
Mixed	−0.38
High	**0.74**
Flat	*−0.13*
Low	*−0.36*

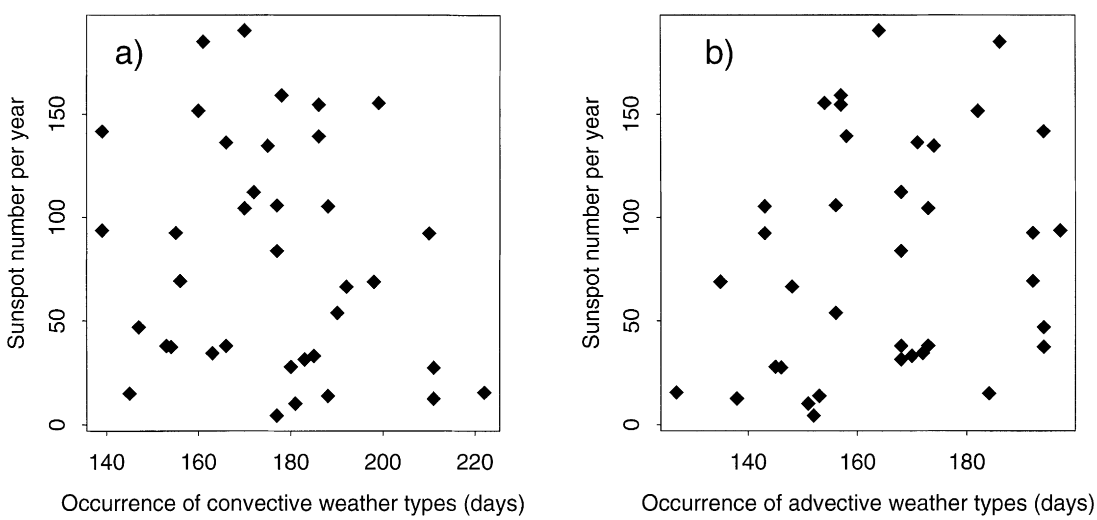

Fig. 7. Annual occurrence of Wolf's sunspot number versus a) the convective weather type and b) the advective weather type

tion of the NAO index and the temperature over Europe.

To find a possible influence of the variability of solar activity on the regional weather types Wolf's sunspot index was compared with the annual occurrences of the weather types. No correlation between the sunspot index and the frequencies of the weather types has been found as Fig. 7 shows for the two main weather classes. Hoyt (1979) suggested the ratio of the umbra-area to the penumbra-area as a measure of the solar activity and found a strong correlation between this ratio and the Northern Hemisphere surface temperature anomalies. However, we have not found significant correlations between this ratio and the occurrence of Schüepp's weather types. Lassen and Friis-Christensen (1995) found a high correlation between the Northern Hemisphere land air temperature and the long-term variability of solar activity represented by the cycle length of the number of sunspots. As only 4 sun cycles occurred since 1945 and as there are only little differences of the length of these cycles an analogous comparison with the occurrence of the weather types is not possible.

6. Conclusions

For the Alpine region, Schüepp (1979) has defined daily synoptic weather types. We analysed their occurrence in the period 1945–1994. The most pronounced finding is the increase of the annual occurrence of convective weather type and the decrease of advective weather type in Switzerland. Most of these changes took place in winter due to an increase of the high pressure weather type and to a simultaneous decrease of the northerly weather type. These frequency changes are mainly caused by a change of the episode lengths rather than by a change of the total number of episodes per year. The average length of convective episodes rose and that of advective episodes fell.

Investigating the relation between local meteorological parameters and Schüepp's classification as a regional parameter, we found a very strong correlation between the locally measured surface pressure and the occurrence of the high pressure weather type, defined from the 500 hPa height. The strong correlation of high pressure weather type with pressure was used for testing the homogeneity of the high pressure weather type time series. No indications of inhomogeneities have been found for high pressure weather type. Although in 1975 several changes of the pressure charts used for the classification have been introduced, this did not lead to a pronounced inhomogeneity of the weather type frequencies (see Fig. 1). At mountain stations correlations between the high pressure weather type and the minimum and maximum temperatures are also high, both, for annual and seasonal means, see Table 7. Correlations between the meteorological parameters and the weather types are in general less pronounced at low altitude stations than at mountain stations indicating stronger local effects at low altitude stations.

The strong correlation of the NAO index with the high pressure weather type confirms that in winters with a high NAO index the westerlies are shifted towards northern Europe and Scandinavia. As most of these frequency changes of the weather types have taken place in winter, it may be that they are caused by the pressure distribution over the Atlantic as described by the NAO index.

Acknowledgement

We thank H. Wanner for bringing several references to our attention and for pointing out the existence of a weak inhomogeneity in the data used. The NAO index was kindly given to us by J. W. Hurrell from the National Center for Atmospheric Research in Boulder. The Schweizerische Meteorologische Anstalt in Zürich made us available the data of the weather types and the meteorological data, the Zentralanstalt für Meteorologie und Geodynamik in Wien the data for the Sonnblick and the Deutsche Wetterdienst in Offenbach the data for the Zugspitze. The data of the solar sunspot numbers are available at Carbon Dioxide Information Analysis Center, Oak Ridge. We thank all of them for giving us access to their data.

Appendix

Schüepp's Weather Types

The synoptic Schüepp weather types (Schüepp, 1978) are manually determined from weather charts according to strict rules. In general, the surface pressure and the 500 hPa heights of 12 UTC are used, from which several coded parameters are deduced for a central region with 444 km diameter around a central point 46°30′ N, 9°E (see Fig. 8). If the parameters cannot be unambiguously determined

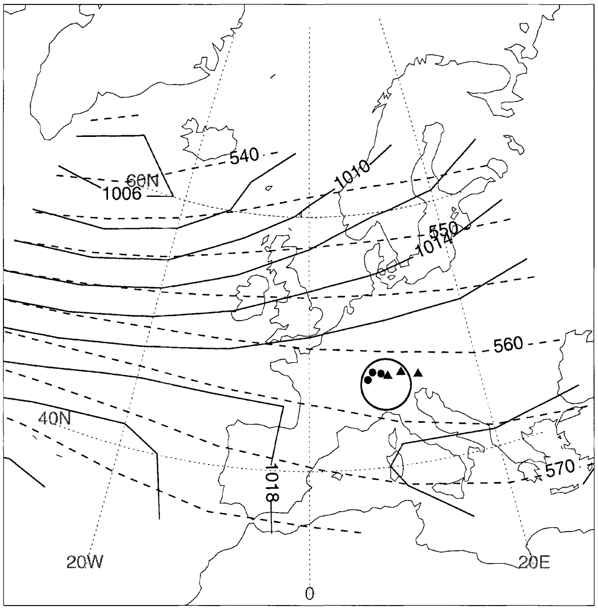

Fig. 8. Mean surface pressure map (solid lines) and mean 500 hPa heights (dashed lines) for the period 1945–1994. The surface pressure is given in hPa, the 500 hPa height in units of 10 gpm. Isobars are 2 hPa apart, isohypses 50 gpm. The circle indicates the region with 444 km diameter around the central point of Schüepp's weather types. The black circles give the location of the low-altitude stations Neuenburg, Basel and Zürich, the triangles indicate the mountain-top stations Säntis, Zugspitze and Sonnblick (from west to east)

from the 12 UTC surface map, the corresponding 850 hPa heights or the 15 UTC or the 9 UTC surface map are additionally taken into account (SMA 1985). For the identification of the 40 weather types of Schüepp five parameters are used: D, the geostrophic wind direction at surface; d, the geostrophic wind direction at the 500 hPa level; f, the wind speed at the 500 hPa level; h, the 500 hPa height; b, the baroclinicity. These parameters are defined as follows:

D: If the surface pressure gradient within the region around the central point is less than 5 hPa/444 km then D = 0. For stronger pressure gradients, eight directions of the resulting geostrophic wind are classified, D = 1, (NE), D = 2 (E), D = 3 (SE), etc. If the isobars around the central point are S-shaped, the upstream wind direction is used as long as the upstream pressure gradient is larger than 5 hPa/444 km, else the wind direction near the central point is used. If within the central region either a saddle point lies, or isobars are closed, or up- and downstream wind directions diverge by more than 90°, the parameter is set to D = 9.

d: It the 500 hPa pressure gradient within the region around the central point is less than 5 hPa/444 km then d = 0. For stronger pressure gradients, eight directions are defined as d = 1 (NE), d = 2 (E), etc. If the 500 hPa wind direction within the central region varies by more than 90°, then d = 9.

f: The 500 hPa wind speed is determined from three radiosoundings in Payerne, Milano and München (with weights 1, 2 and 1). f = 0 for a speed of 0–9 knots, f = 1 for 10–19 knots, etc., and f = 9 for speeds $\geq$ 90 knots.

h: The geopotential height is calculated from the three radiosoundings in Payerne, Milano and München (with weight 1, 2 and 1). The mean annual distribution of the 500 hPa heights is used to determine whether the height is normal, above or below normal.

b: If the angle between surface isobars and 500 hPa contours is less than 45°, the situation is classified as barotropic, else as baroclinic.

The scheme for all 40 weather types is given in (SMA, 1985, Wanner et al., 1998). As only the coarser division into three main types and 7 subclasses is discussed in the present paper, only their identification scheme is shown in Table 9.

The Schüepp weather types are mainly determined from data within a small region of 444 km around the central point (indicated by the circle in Fig. 8). To gain some insight how the synoptic situation over Europe looks like for the different weather types, the daily surface pressure maps and the 500 hPa heights from 1945–1994 (SMA, 1985) were stratified according to the weather types and mean

Table 9. *Specification of the 8 Main Weather Types in Terms of the Parameters Described in Text. The Surface and 500 hPa Wind Directions D and d are Coded as 1 (NE), 2 (E), 3 (SE), 4 (S), 5 (SW), 6 (W), 7 (NW), 8 (N)*

Main class	Main type	D	d	f	h
Convective	High	0	0–9	$\leq$4	4th quartile
	Flat	0	0–9	$\leq$4	2nd and 3rd quartile
	Low	0	0–9	$\leq$4	1st quartile
Advective	West	1–8	6	all	all
	North	1–8	7–9	all	all
	East	1–8	1–3	all	all
	South	1–8	4–5	all	all
Mixed	Mixed	9	all	all	all
		or 0	all	$\geq$5	all
		or 1–8	0	4	all

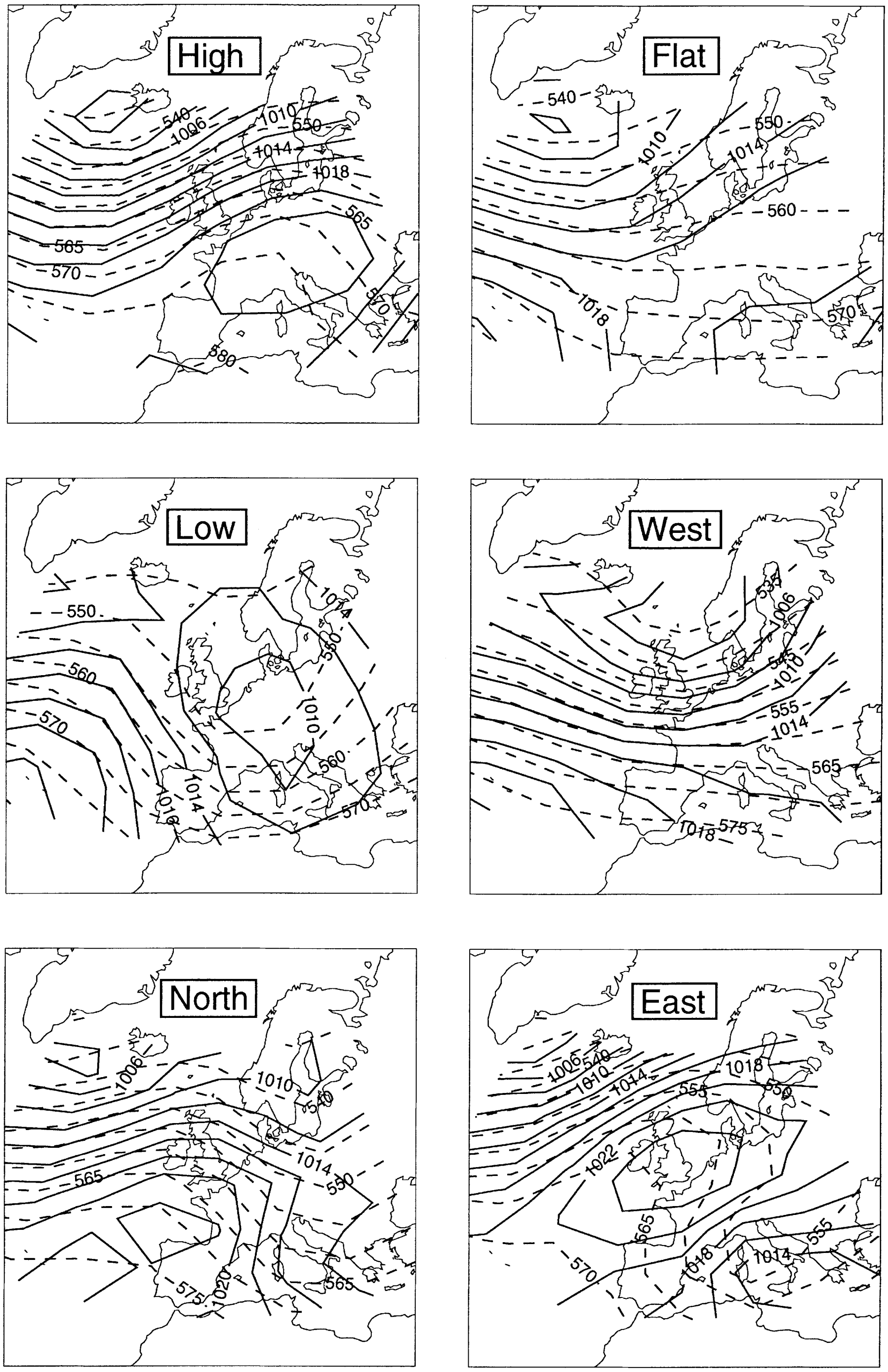

Fig. 9. Composite mean surface pressure map (solid lines) and mean 500 hPa heights (dashed lines) for the period 1945–1994 for the eight main weather types and the convective and advective situations. The surface pressure is given in hPa, the 500 hPa height in units of 10 gpm. Isobars are 2 hPa apart, isohypses 50 gpm

maps for each weather type were formed. Figure 8 shows the resulting composite mean for all days of the 50 year period. A south-north gradient can be observed both in the surface pressure as well as in the 500 hPa heights. Over the Atlantic the pressure gradient is stronger than over the continent. The surface map shows also a region with lower pressure over the western Mediterranean. These features are also present as background in the maps of the individual weather types. Figure 9 shows the composite means of the three main weather types and the seven subclasses. Similar seasonal pressure maps for some of the 40 weather types are shown in Schüepp (1979). During high pressure situations a pronounced surface high is centered around the central point, associated with a high of the 500 hPa level shifted to the southwest. Situations with flat pressure distribution resemble very much the overall mean pressure distribution shown in Fig. 8. Low pressure types have a pronounced surface low situated over the central point and a 500 hPa low shifted to the north. For westerly situations a strong meridional pressure gradient is present over the

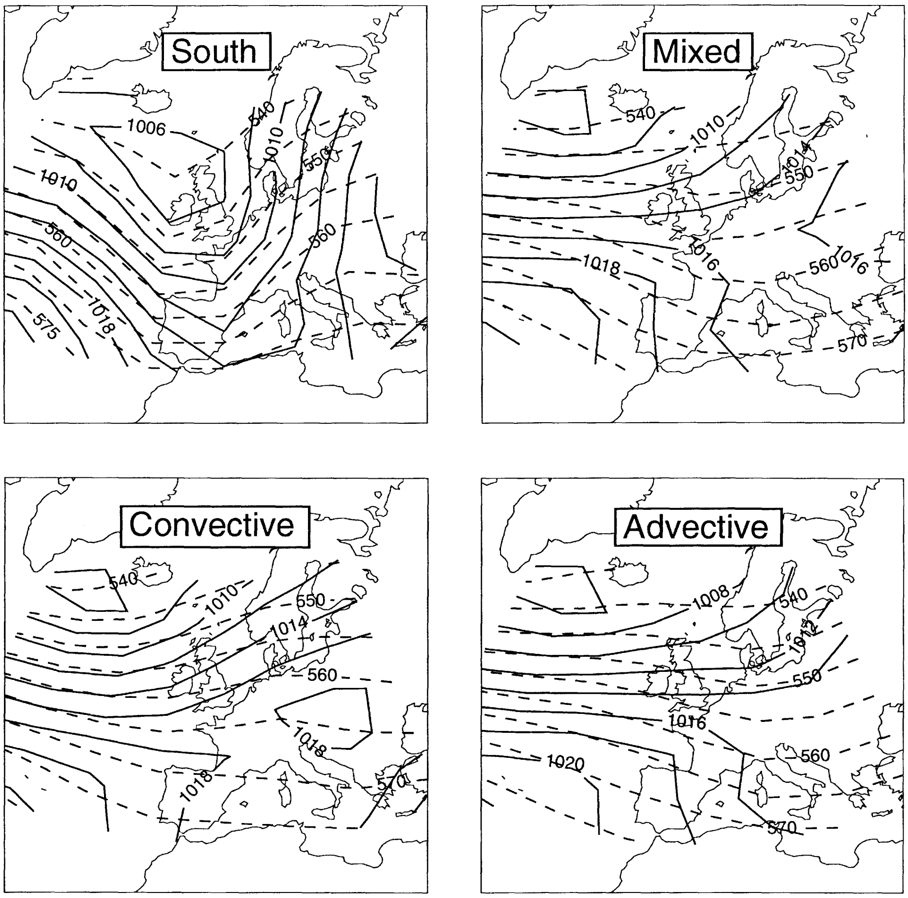

Fig. 9 (*continued*)

central region with nearly parallel isolines in the surface and the height map. For northerly and easterly weather types a surface high is present over the gulf of Biskaya or the channel, respectively. The southerly weather types are caused by a low over the British Isles. The mixed weather type on average has a flat pressure distribution over the central region with strong baroclinicity. As high and flat pressure distribution are the most frequent convective weather types (Table 1) the mean map of the convective types is a superposition of high and flat maps. Similarly, the mean map of advective situations is mainly determined by a superposition of northerly and westerly weather types, the most frequent advective types.

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