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Recent Variations of Snowpack Depth in the Central Spanish Pyrenees

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Abstract

The evolution of snow depth in the central Spanish Pyrenees was analyzed using measurements from 106 snow stakes over a period of 14 yr (1985–1999). Relationships were considered between the regional series of snow depths at the end of winter and in the middle of spring with respect to precipitation and temperature in previous months. Both variables explained a large percentage of the interannual variability in snowpack. The high correlation between climate parameters and snow depth series may help to better understanding snow evolution at different times of the year and to obtain a predicted series of snow depths for the period 1950–1999 from longer climate series. Snow depth decreased significantly during the second half of 20th century, probably because there was less precipitation from January to March. The decrease in winter precipitation seemed to be related with the positive trend of the North Atlantic Oscillation (NAO) index during the same period.

Introduction

Water stored in winter snowpack in mountainous areas is a valuable resource (Changnon et al., 1993). Interannual and long-term evolution of snowpack determines the availability of water resources during the snowmelt period (Roger and Harrington, 1995; Chorley, 1969; Pupacko, 1993; Katwijk and Childress, 1994), as well as the development economic activities based on winter sports (Breiling and Charamza, 1999; Bürki et al., 2003).

Many authors have stressed the importance of spatial and temporal patterns of snowpack and the processes which control snowmelt (Aizen et al., 1996; Bales and Harrington, 1995; Karl et al., 1993; Hsieh and Tang, 2001). Nevertheless, the procedures to assess snow distribution and snow water equivalent are difficult to apply to large areas and the results are not always satisfactory (Dunne and Leopold, 1978; Zuzel and Cox, 1975). The topography of mountain basins is highly variable, which increases the heterogeneity of the variables controlling snow accumulation and melt. Furthermore, one of the main problems in snow studies is the difficulty of obtaining snow and climate data from large areas in winter and spring. Unfortunately, it is not easy to establish a dense network of well-equipped weather stations in high mountain areas (air and soil temperature, precipitation, cloudiness, solar radiation at different wavelengths, wind direction and velocity, etc).

In this paper the evolution of snow depth is discussed in terms of precipitation and air temperature, which are usually the only variables available on a large scale. The main purpose of this study was to obtain a series of predicted snow-depth values in order to asses the existence of a temporal trend in snow accumulation over a long period (1950–1999).

Study Area

The study area is located between the Aragón and Noguera Ribagorzana rivers in the Central Spanish Pyrenees (Fig. 1). The relief increases progressively eastward and northward. The highest altitudes are at the headwaters of the river Cinca, Ésera, and Noguera Ribagorzana rivers.

The structure of the relief is organized in parallel bands from north to south. The following structured areas can be distinguished: (1) the Axial Pyrenees made up of paleozoic materials (limestone, slates, quarzites) and granitic batholiths (with the gniess peaks in the study area; Aneto peak, 3404 m a.s.l. and Posets peak, 3365 m); (2) the Inner Sierras made up of mesozoic materials (basically limestone and sandstones) which form an abrupt relief, frequently exceeding 3000 m a.s.l.; and (3) the Flysch Sector composed of sandstones and Eocene marls alternating in very thin beds with maximum altitudes around 2000 m (García-Ruiz et al., 2001).

The gradient of temperatures and precipitation is north–south and west–east, as a result of Atlantic and Mediterranean influences. The Atlantic influence dominates in the western sectors of the study area and is progressively substituted by Mediterranean or Continental-Mediterranean influences. The topographic heterogeneity partly explains the large spatial variability in annual precipitation. The areas above 2000 m a.s.l. receive more than 2000 mm yr^{-1}, and around 2500 mm in the highest divides (Rijckborst, 1967; García-Ruiz et al., 2001). Most of the precipitation falls in autumn and spring (García-Ruiz et al., 2001). The summer is relatively dry (with the occasional rainstorm), as well as the winter (snowfalls alternate with long anticyclonic periods). In the westernmost part of the study area, the winter is more humid since it is continuously exposed to oceanic fronts.

Temperatures are mainly dictated by the altitudinal gradient. Above 1000 m a.s.l. the average annual temperature is lower than 10°C. At 2000 m a.s.l. the temperature is around 5°C (Puigdefábregas and Creus, 1973). Between November and April the 0°C isotherm is around 1600 m a.s.l. (García-Ruiz et al., 1986), which is why the winter snowpack remains constant above this altitude. The lowest altitude for the 0°C isotherm is in February when snow cover is maximum, until around 1600 m a.s.l. Isolated snowpatches may persist in shady aspects until June and July.

Methods

The seasonal and interannual evolution of snowpack was measured using 106 snow stakes installed in the study area since 1985. Snow stakes remain installed throughout the year: They are made of fiberglass and are inserted in a concrete base. They are 4 m height, and are subdivided in bands of 50 cm of different colors to facilitate measurement. The location of the snow stakes (Fig. 1) aims

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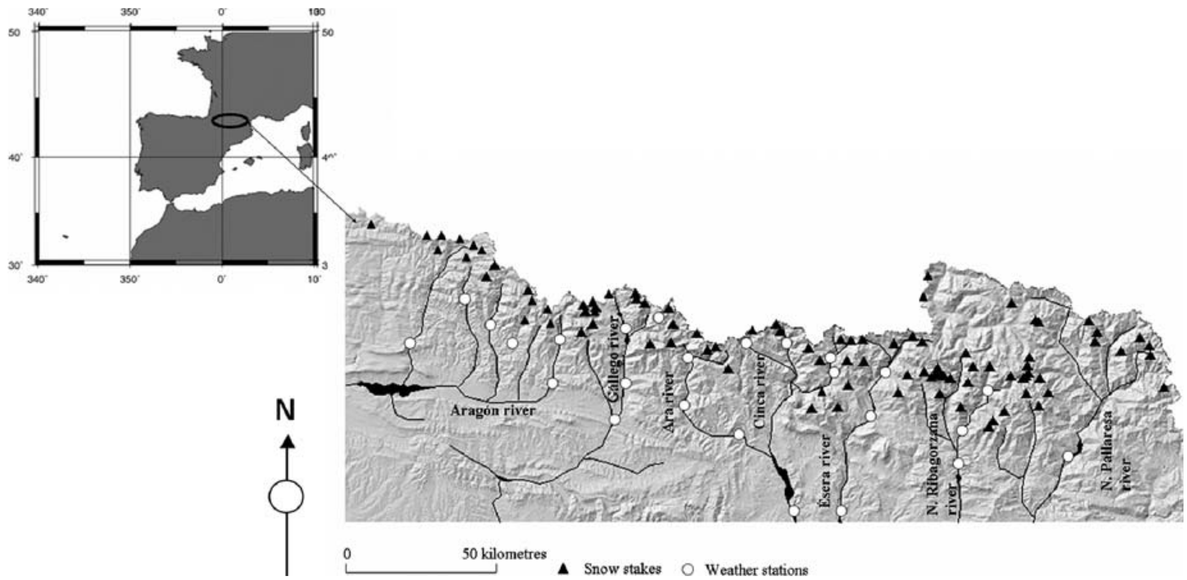

FIGURE 1. Study area. Location of the selected snow stakes and weather stations.

the representativeness of large areas, avoiding possible local anomalies caused by wind or snow avalanches. The effect of the wind on snow redistribution is the major potential error; which is mostly solved in the process of control of quality data. Snow depth was measured at the beginning of March and the end of April or beginning of May. Sometimes weather conditions required slight changes in the measurement dates. No measurements could be taken in March 1991. The snow stakes were installed and managed under the ERHIN Program (Estudio de los Recursos Hídricos Invernales: Study of winter water resources), which aimed to quantify water resources related to snow accumulation in northern Spain. It is financed by the Office of Hydraulic Works, under the Ministry of Environment. Data before 1994 were published annually (Pedrero and Arenillas, 1992–1997) and afterwards provided directly by the ERHIN Program.

Eighty-four snow stakes were chosen for the March calculation and 79 for the end of April–beginning of May in order to comply with the following statistical requirements:

(1) To obtain at least 11 yr of measurements for each snow stake in order to cover the longest study period with the highest number of snow stakes. An increase in the years considered sharply reduced the number of available snow stakes. Most of snow stakes rejected had too short data sets. Only 30 snow stakes of March and 33 of April–beginning of May showed a complete data set. For the rest, missing data in the series were obtained by applying a linear regression with the values of the nearest snow stakes that were correlated by more than $r^2 = 0.7$.
(2) The data must be fitted to a normal distribution according to the Shapiro-Wilks test. Only information from two snow stakes by the end of April–beginning of May was rejected for this reason.
(3) Each snow stake must be correlated significantly with the rest of snow stakes of the study area. This procedure enabled detection of a reduced number of locations that seemed to be affected by local conditions without relation with the general pattern of the study area.

A regional series of anomalies in snow depth was obtained from 1985–1999 (hydrological years) using the selected snow stakes for each measurement period (March and end April–beginning May). The result is two synthetic regional indexes with a zero mean and one unit of standard deviation expressed in z scores that summarized the regional anomalies above or below the average.

Precipitation and temperature data were obtained from 24 and 17 weather stations, respectively. A reference period from 1985 to 1999 was used to correlate with the snow depth series. Then a longer period (1950–1999) was used to obtain a series of temperature and precipitation anomalies in order to construct a longer series of snow depths.

Relationships between the evolution of climatic variables and snow depth were assessed by a stepwise multiple regression model. We only included predictor variables that significantly improved the explanation of the dependent variable and that provided information about the proportion of the variance explained by each variable. Some analyses distinguished between the snow stakes above or below 2200 m a.s.l. in order to discriminate between the snowpack behavior in the highest and lowest altitudes. This threshold was chosen since it is a clear geomorphologic and biogeographic limit in the Central Pyrenees (García-Ruiz et al., 1990).

The altitude of the snow stakes ranges between 1750 and 2750 m a.s.l. It was not possible to consider the evolution of snow accumulation below 1750 m with the available information. The characteristics of sectors above 2750 m were assumed to be similar to the highest snow stakes, with a delay at the beginning of the snowmelt season.

The temporal trends in climatic and predicted snow depth series (1950–1999) were analyzed using a parametric test (Pearson's correlation coefficient) since the series were fitted to a normal distribution. Nonparametric tests (Spearman's rho and Kendall's tau-b) were used to compare the results obtained by the different methods. The trend observed in precipitation was compared with the monthly and seasonal trend of the North Atlantic Oscillation (NAO) index, defined as the normalized Lisbon (Portugal) minus Stykkisholmur (Iceland) sea-level pressures (provided by Jim Hurrell, www.cgd.ucar.edu/~jhurrell/).

Results and Discussion

TEMPORAL VARIABILITY OF SNOWPACK

The spatial and temporal variability of snow depth was quite high. Figure 2 shows the frequency distribution of the average snow depths.

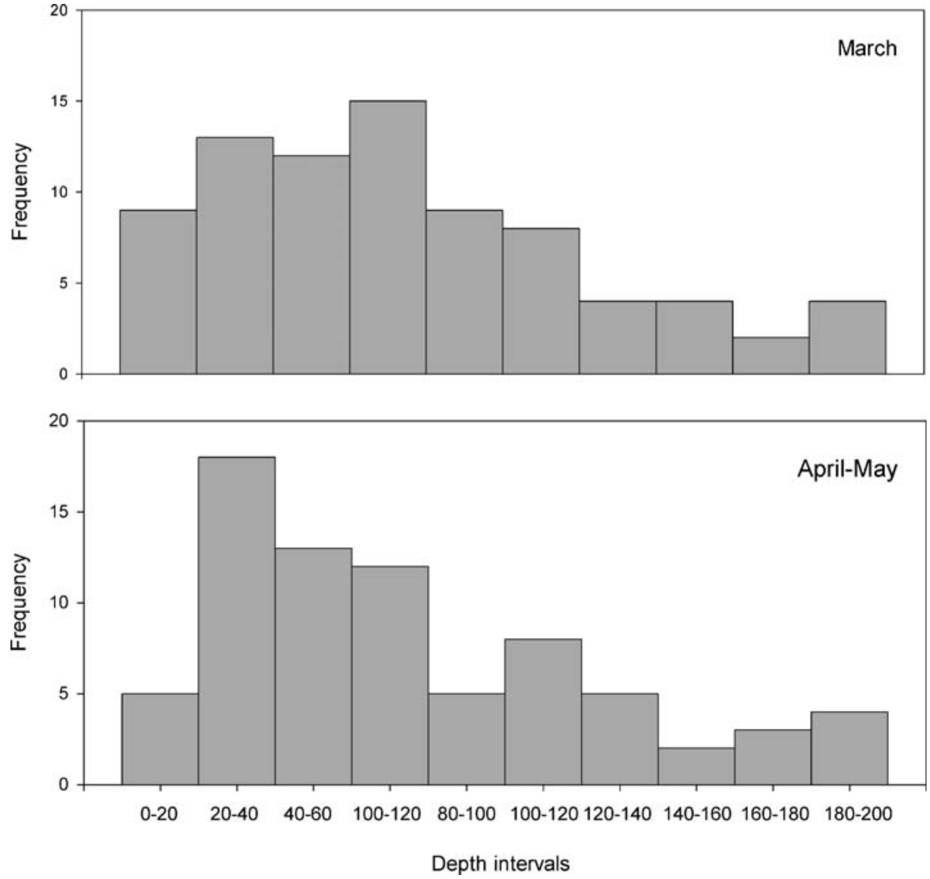

FIGURE 2. Frequency histograms of the average snow depth.

The highest frequency was between 20 and 80 cm, although many exceeded 100 cm or even 200 cm.

Snow depth differed substantially among snow stakes due to a pronounced interannual variability. Values as high as 400 cm were recorded after heavy snowfall, while in dry winters some areas were free of snow. The high interannual variability is confirmed by a mean variation coefficients of 0. 78 for March and 0.72 for April.

Figure 3 shows the depth anomalies at the beginning of March and the end of April. March and April often have large fluctuations in snow depth. In general, an agreement between both periods of measurement can be observed, though in recent years April seems to have larger oscillations between years than March. For example, there were important negative anomalies at the end of April in 1994 and 1996, contrasting with values in March.

In order to describe the relationships between snowpack evolution and the most outstanding climatic conditions in previous months, we took into account the precipitation and temperature series for different time intervals before March and May as predictor variables of snow accumulation. The rainfall series for December–February, December–March, December–April, January–March, and January–April were used as well as the mean temperature of January, February, March, April, December–March, January–March, December–April, and January–April.

There was a highly significant correlation between both snow depth series and the accumulated precipitation in previous months (Table 1). The precipitation from December to February explained a large part of the variance in snow depth in March, while at the end of April or beginning of May the most important variable was precipitation between January and April.

It is very interesting to note that there was no significant correlation between temperature and snow depth in March, while the average April temperature was negatively correlated with snow depth in the middle of spring.

Thus, between December and March most of precipitation fell as snow over 1600 m a.s.l. The temperature has no influence since snowmelt had not started. In April–May, temperature determined the proportion of snowfall and rainfall and the velocity of snowmelt.

The different role of precipitation and temperature in March and April is confirmed in Table 2 (for snow stakes above or below 2200 m). The regressions corresponding to March include in the three cases the precipitation that fell in winter with a similar capacity to explain the variance of the dependent variable (r^2 around 0, 65). Temperature was not an important factor at any altitude regarding snow depth in March.

In April–May the capacity of precipitation and temperature to explain the variance of snow depth varied in terms of altitude. The determination coefficient was very similar in the three cases (around 0.7), but the beta coefficients and the percentage of variance explained by each variable was different for the snow stakes located above and below 2200 m a.s.l. The beta coefficient of average temperature was higher for snow stakes below 2200 m a.s.l. Furthermore, in the lowest sectors, precipitation only explained 34% of the variance of the dependent variable, while temperature explained 47%. The contrary occurs above 2200 m where precipitation from the previous months explains 44% of the variance and temperature only 23%. Thus, the average temperature in April explained the snowpack evolution at any altitude but its influence was much higher below 2200 m.

Figure 4 shows the evolution of snowpack in April–May in relation to the altitude. Approximately 90% of all the snow stakes oscillated between an increase of 25.3 cm and a decrease of –27.3 cm. The average value of depth variation was –1.77 cm. The snowpack decreased an average of 17.4 cm for the snow stakes below 2200 m

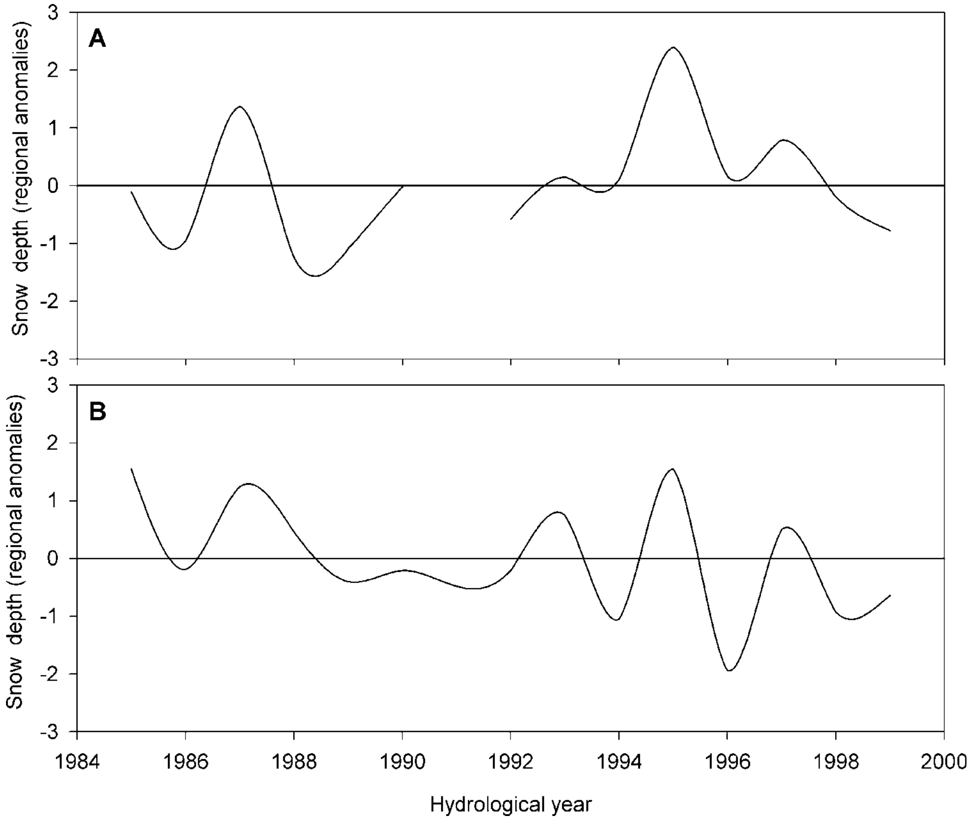

FIGURE 3. Regional series of snow depth. A. Beginning of March. B. End of April–beginning of May.

a.s.l. Ninety percent of the snow stakes oscillated between an increase of 6.7 cm and a decrease of 41.2 cm. In the upper sector, the snowpack continued to grow 9.7 cm on average; 90% of the snow stakes oscillated between 29.3 and –5.7 cm. These figures confirm that snowmelt was already active in April–May below 2200 m, due to the increase in temperature. Above 2200 m, snow accumulation continued in spite of increasing temperatures.

TABLE 1

Correlation coefficients between snow depth and climatic variables.

	Pearson's correlation coefficient
Snow depth in March	
Ppt (Dec–Feb)	0.82*←
Ppt (Dec–Mar)	0.79*
Ppt (Jan–Mar)	0.78*
T (Dec–Feb)	0.01
T (Dec–Mar)	0.05
T (Jan–Mar)	0.04
T Feb	−0.25
T Mar	−0.25
Snow depth in April–May	
Ppt (Dec–Mar)	0.62*
Ppt (Jan–Mar)	0.63*
Ppt (Dec–Apr)	0.69*
Ppt (Jan–Apr)	0.72*←
T (Dec–Mar)	0.17
T (Dec–Apr)	0.01
T (Jan–Apr)	−0.19
T Apr	−0.39*←

* Correlation is significant at 0.05.

← Variable introduced in the stepwise regression model.

Ppt = precipitation, T = temperature.

TRENDS IN SNOW ACCUMULATION DURING THE PERIOD 1950–1999

A stepwise regression model was constructed from Table 1 to predict long series of snow depth. Figure 5 shows the real values of snow depth between 1985 and 1999 in March and April–May. The reconstructed series from 1950 to 1999 were plotted showing the good fit between the observed and the predicted values ($r^2 = 0.68$ for March, and $r^2 = 0.72$ for April–May). According to the regression model, snow accumulation is characterized by (1) large fluctuations, especially in April–May, (2) a long period of relatively high snow accumulation until 1978, and (3) the existence of a slight negative trend in both March and April–May.

Table 3 shows the coefficients obtained in the different parametric and nonparametric trend tests applied to the predicted snow depth series and to different climatic variables. The correlation coefficients confirm a decrease in the snow depth values from 1950–1999 (statistically significant in both series). The coefficients of monthly precipitation were always negative and significant from February to March. The precipitation decreased strongly in March with highly significant coefficients in all the tests used. In February there was a positive correlation with temperature (Pearson's correlation coefficient), which may imply an increase in the altitude of the lower limit of the snowpack, or a decrease of snowfall days (especially critical around the 0°C isotherm).

The trend in the accumulated precipitation from December to February and from January to April was also significantly negative, even if there was no significant trend in some individual months. These results explain most of the predicted snow depth in both March and April–May.

The negative trend in the evolution of predicted snow depth values is a response to the changes in winter climatic variables. Several authors have stressed the relationship between the recent evolution of winter precipitation in Southern European regions and

TABLE 2

Statistics of the regressions between snow depth and climate variables for different altitudinal levels.

Month of measurement	Snow stakes used	R	R^2	Explained variance by precipitation (%)	Explained variance by temperature (%)	Beta coefficients precipitation	Beta coefficients temperature
March	All the stakes	0.82	0.67	67	—	0.82	—
	Stakes below 2200 m	0.8	0.65	65	—	0.8	—
	Stakes above 2200 m	0.79	0.62	62	—	0.79	—
April–May	All the stakes	0.85	0.72	51	21	0.76	−0.44
	Stakes below 2200 m	0.84	0.71	34	47	0.64	−0.61
	Stakes above 2200 m	0.82	0.68	44	23	0.7	−0.48

the NAO index (Hurrell and Van Loon, 1997; Mächel et al., 1998; Tomasino and Dalla-Valle, 2002). The North Atlantic Oscillation explains most of winter climatic variability in the North Atlantic region (Lamb and Peppler, 1987; Hurrell, 1995; Hurrell and Van Loon 1997; Trigo and Palutikof, 2001) and, also, in the Iberian Peninsula (Rodriguez-Puebla et al., 2001; Martin-Vide and Fernández-Belmonte, 2001; Goodess and Jones, 2002; Rasilla-Alvarez and Fernandez-García, 2002; Dünkeloh and Jacobeit, 2003; Uvo, 2003; Trigo et al., 2004). The evolution of winter precipitation during the last decades in the Pyrenees shows similarities with the negative trend observed in the southern Mediterranean areas (Dünkeloh and Jacobeit, 2003).

In the Iberian Peninsula, there is a strong negative correlation between NAO index and the frequency of cyclonic and synoptic situations related to southwest, west, and northwest influences (Rogers, 1997; Corte-Real et al., 1998; Vicente-Serrano, 2004), which are prone to produce precipitation in winter (Gonzalez-Rouco et al., 2000; Trigo and Da Camara, 2000; Vicente-Serrano, 2004). This fact explains the negative correlation between NAO index and monthly precipitation from December to March in the Pyrenees (Table 4). The correlations shown in Table 4 confirm that precipitation decreases only during the months with a significant positive trend evolution of NAO index (Table 5). Similarly, a strong relationship observed at a monthly basis is detected for the intervals December–February and January–April, which explains the decrease of snowpack in the Pyrenees.

The effect of the positive trend of NAO index on the reduction of snowpack has also been analyzed in other southern European mountain ranges, especially in the Alps. Several authors (Martin et al., 1994; Beniston, 1997, 2003; Breiling and Charamza, 1999; Beniston et al., 2003) show a decrease in snow thickness and snow cover in the French, Swiss, and Austrian Alps, especially in the lower and southern areas. The opposite influence of the NAO index on climate in northern Europe (Hurrell, 1995) explains the major role of the Icelandic low pressures in the last decades. It led to an increase in winter precipitation, which caused more abundant snowfalls in the areas above 0°C isotherm (Hyvärinen, 2003). However, in these areas increasing temperatures correlate with a decrease of snowfalls and snow cover. Thus, Jaagus (1997) and Bednorz (2002) suggest that the increase of cyclonic activity in Estonia and Poland, respectively, as a consequence of the evolution of NAO index, have implied an increase of winter temperatures and therefore a decrease of the winter snow cover.

A decrease of snow accumulation has strong implications on different issues such as the phenology of plant and animals, runoff generation, and seasonal flood distribution (Barry, 1992; Bales and Harrington, 1995; Beniston, 1997; Nijssen et al., 2001; Krasovskaia and Gottschalk, 2002). In the Pyrenees, a noticeable decrease in spring flows has been detected, but no trend in the seasonal precipitation evolution was found, suggesting important changes in snowmelt processes (López-Moreno and García-Ruiz, 2004). This fact has a paramount importance on water resources management since snowmelt is a key factor to supply water to lowlands in the Mediterranean regions (López-Moreno et al., 2002, 2004). Furthermore, both, the negative trend in snow thickness or the increase in the lower altitudinal limit of winter snow cover has a negative effect on many economic activities (Jaagus, 1997; Breiling and Charamza, 1999; Bürki et al., 2003). In the Pyrenees, as in other mountainous areas, the local economy has been fundamentally altered in recent decades by the progressive replacement of agricultural activities by the tourist industry (García-Ruiz and Lasanta-Martinez, 1990, 1993; Laguna and Lasanta-Martinez, 2003). Tourism is mainly based on winter sports, which directly depend on the amount and duration of the snowpack. Consequently, changes on snow accumulation could lead to noticeable impacts on the economy of the Pyrenean valleys.

Conclusions

Snow accumulation is of paramount importance in the Central Spanish Pyrenees. Many features of river regimes are related to winter snow retention and spring snowmelt (García-Ruiz et al., 2001), and the patterns of reservoir management are partially controlled by the expectations of snowmelt (López-Moreno et al., 2002; 2004). However, some snow parameters must be deduced indirectly (especially from hydrological features) due to the lack of high mountain weather stations (García-Ruiz et al., 1986). In 1986, 106 snow stakes were installed under the ERHIN program to measure the evolution of snow accumulation at different altitudes and valleys. This information has been used in this paper to identify the factors that best explain snow accumulation in March and April–May, and to reconstruct a long series of snow accumulations in order to detect any temporal trend.

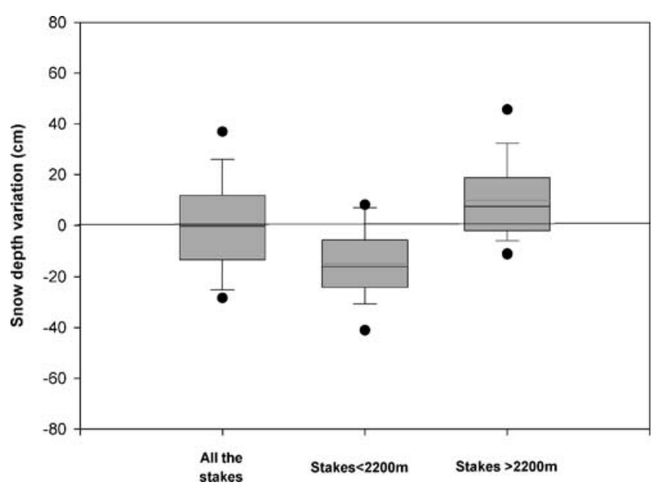

FIGURE 4. Average snow depth variation in April from 1985–1999.

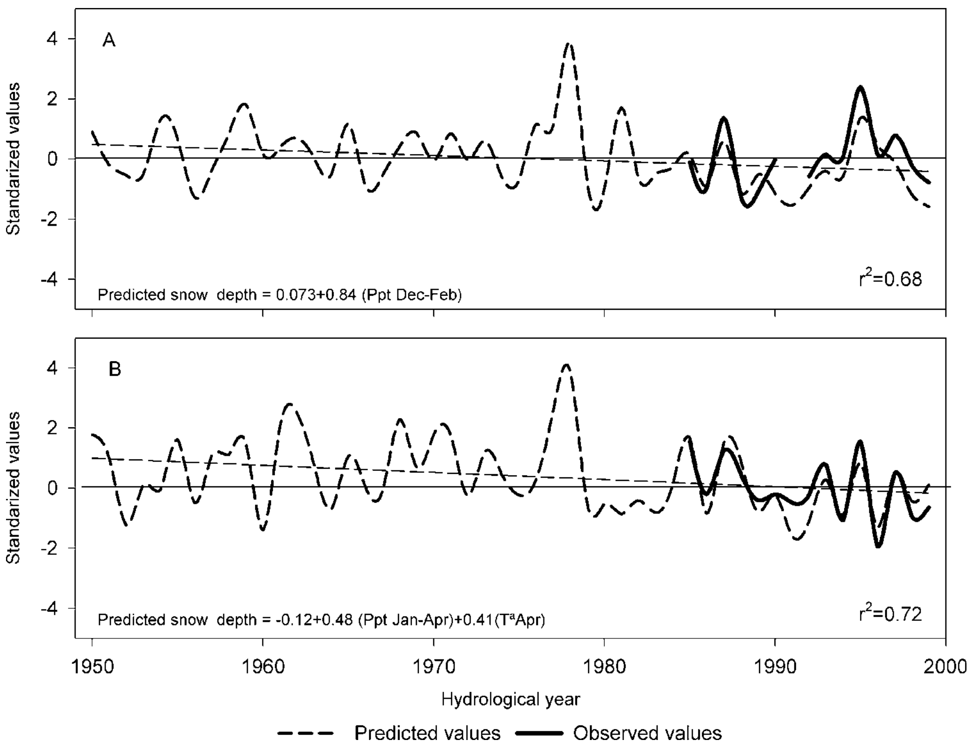

FIGURE 5. Predicted series of snow depths obtained by stepwise regression and correspondence with the observed series. A. Beginning of March. B. End of April–beginning of May.

The main conclusions are:

(1) Highly significant correlations were found between snow depth in March and April–May and the accumulated precipitation of previous months (i.e., December to February in the case of March, and January to April in the case of April–May).

(2) Temperature only influenced snow depth significantly in April–May, especially in the lower altitudes of the study area (around 1700–2200 m), whereas in March the snow depth was only controlled by previous precipitation, without any influence of temperature. The reason for this difference is that snowmelt begins in April in most of the Pyrenees and is directly controlled by temperature (García-Ruiz et al., 2001).

(3) A regression model was developed including the most significant climatic variables. The good adjustment between predicted and observed series from 1985–1999 allows us to enlarge the predicted series of snow depth to 1950–1999.

These series are long enough to apply different trend analysis showing a statistically significant decrease in the study area. The decrease of snow depth is related to the decrease in precipitation in February and March associated with a positive trend of the NAO index. Finally, April shows a positive, no significant, trend in precipitation as well as a decrease in temperature.

A decrease in winter snow accumulation may produce several impacts on both (1) the availability and management practices of water resources, and (2) the economy of the Pyrenean valleys mostly based on winter tourism.

TABLE 3

Trends in the series of predicted snow depth values and different climatic series for the period 1950–1999. The three last variables are those included in the stepwise regression model.

	Pearson's correlation coefficient	Spearman's rho	Kendall's tau-b
Predicted snow depth in Mar	−0.26*	−0.23*	−0.33*
Predicted snow depth in Apr–May	−0.32*	−0.29*	−0.45*
Ppt Dec	0.06	−0.10	−0.14
Ppt Jan	−0.15	−0.21	−0.16
Ppt Feb	−0.36*	−0.35*	−0.24*
Ppt Mar	−0.47*	−0.48*	−0.34*
Ppt Apr	0.22	0.16	0.11
T Dec	−0.02	−0.01	−0.02
T Jan	−0.12	0.06	−0.04
T Feb	0.29*	0.28	0.19
T Mar	0.08	0.18	0.11
Ppt Dec–Feb	−0.26*	−0.32*	−0.22*
Ppt Jan–Apr	−0.42*	−0.40*	−0.25*
T Apr	−0.36*	−0.31*	−0.22*

* Correlation is significant at 0.05.

Ppt = precipitation, T = temperature.

Acknowledgments

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TABLE 4

Correlation coefficients between precipitation and NAO index.

	Pearson's coefficient	Spearman's rho	Kendall's tau-b
Dec	−0.42*	−0.39*	−0.28*
Jan	−0.36*	−0.31*	−0.21*
Feb	−0.49*	−0.46*	−0.35*
Mar	−0.61*	−0.57*	−0.41*
Apr	−0.21	−0.18	−0.13
Dec–Feb	−0.60*	−0.61*	−0.42*
Jan–Apr	−0.57*	−0.59*	−0.43*

* Correlation is significant at 0.05.

TABLE 5

Trends in monthly precipitation and the NAO index.

	Pearson's correlation coefficient		Spearman's rho		Kendall's tau-b	
	Precipitation	NAO index	Precipitation	NAO index	Precipitation	NAO index
Dec	0.06	−0.02	0.1	−0.07	−0.14	−0.01
Jan	−0.14	0.19	−0.21	0.19	−0.14	0.13
Feb	−0.36*	0.41*	−0.35*	0.39*	−0.24*	0.27*
Mar	−0.47*	0.45*	−0.48*	0.41*	−0.34*	0.29*
Apr	0.26	0.03	0.16	0.02	0.11	0.02
Dec–Feb	−0.26*	0.29*	−0.33*	0.31*	−0.23*	0.21*
Jan–Apr	−0.42*	0.46*	−0.45*	0.45*	−0.29*	0.31*

* Correlation is significant at 0.05.

of sediment in sustainability" (WARMICE, ENV4-CT98-0789), funded by the European Community, "Permanent stations to study hydrological processes in Mediterranean environments" (EPROHIDRO, HID98-1056-C02-01), and "Hydrological and erosion processes in Pyrenean catchments in relation to land-use changes and climate variability" (REN2003-08678/HID), both funded by CICYT.

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