Climatological comparison of 2011-2012 and 2012-2013 snow seasons in Central and Western Spanish Pyrenees and its relationship with the North Atlantic Oscillation (NAO)

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ABSTRACT: The 2011–2012 winter season can be considered exceptional in Spanish Central and Western Pyrenees due to the scarce precipitation and unconsolidated snowpack. However, the 2012-2013 winter season was highlighted by the intensity and duration of snowfall episodes, specially in January and February. Snowpacks depths around 4 metres have been reported in several stations at altitudes of more than 2000 m.a.s.l. and depths over 2 metres in stations at altitudes between 1300 and 2000 m.a.s.l.
Different weather and snow parameters (temperature, precipitation, snowfall, number of snow days, snowpack depth) have been taken into account to compare these two seasons. A possible influence of the North Atlantic Oscillation (NAO) teleconnection pattern in the different behaviour of the two winter seasons has been analyzed, demonstrating a clear relationship. All weather and snow data are provided from AEMET nivometeorological stations network in the Central and Western Spanish Pyrenees range, which are also presented in this work.

KEYWORDS: Snow accumulation, Number of Snow Days (NSD), Persistence of snow, North Atlantic Oscillation (NAO), Spanish Pyrenees.

1 INTRODUCTION

An analysis of 2011/2012 and 2012/2013 snow seasons was made in the Pyrenees of Navarre and Aragon (Spain). The main objective is to highlight the contrast between the two seasons, trying to find a relationship with the North Atlantic Oscillation (NAO).

2 STUDY AREA AND DATA

The Pyrenees mountain range is located in the north of the Iberian Peninsula (Figure 1) and includes territories of three neighboring countries: France, Spain and Andorra. Spanish Pyrenees are located on the south side of the watershed and they are divided in three subdivisions: Western, Central and Eastern. Our study area is focused on the Western and Central Pyrenees.

The relief in this area is configured by different massifs separated by valleys perpendicular to its main axis of direction W-E. Elevation in this region increases eastward to slightly exceed 3000 m above sea level (m.a.s.l.) in the highest peaks, reaching the maximum altitude in the Aneto Peak (3404m.a.s.l.).

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The climate of the study area is conditioned by its location on the so-called temperate zone, approximately between parallels 42° and 43° N latitude, with predominantly westerly winds, in addition to its altitude and other factors. This fact, together with the barrier effect exerted by the zonal arrangement relief, produces climatic differences between areas with high and lower Atlantic influence, generally, from west to east. Most of the weather disturbances that affect it exhibit an Atlantic origin with variable synoptic flows from southwest to northwest.

The data analyzed in this work come from the nivometeorological network of Spanish State Meteorological Agency (AEMET). Observations started at Góriz mountain refuge in 1981 and continue until today. A climate reference series (1981-2011) for snow season precipitation and temperature is available in this station. Percentils were calculated with empirical data in order to characterize the thermopluviometric behaviour of both snow seasons in Góriz. Climatic series was divided into quintils, obtaining different possible behaviours in the corresponding month or season:

- Extremely cold/dry: its value is lower than the minimum of the reference period.
- Very cold/dry: below the 20th percentil.
- Cold/dry: between the 20th and the 40th.
- Normal: between the 40th and 60th.
- Warm/wet: between the 60th and 80th.

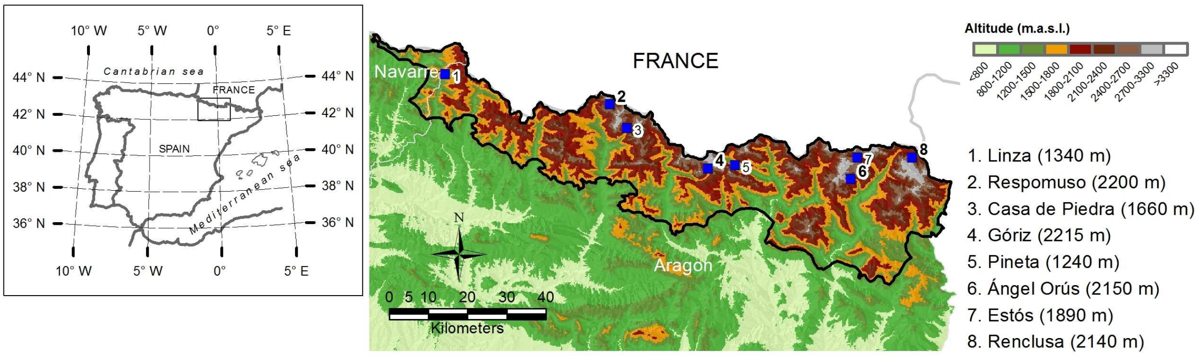

Figure 1. Location of the study area in the northern Iberian Peninsula. Numbers indicate location of weather stations analysed in this study.

- Very warm/wet: above the 80th.
- Extremely warm/wet: its value overcomes the maximum value of the reference period.

The network has been gradually expanding. Currently, in the study area, the network consists of 16 manual observatories located in mountain refuges belonging to the Aragonese Mountaineering Federation (FAM), ski resorts of the Aramon Group, as well as Linza Refuge and Candanchú Ski resort. They cover a wide altitudinal range with stations between 1200 and 2200 m.a.s.l. Four high mountain weather stations around 2200 m.a.s.l. with a continuous data recording were selected for the core study: Respomuso, Góriz, Ángel Orús and La Renclusa. Furthermore, reference is made to other stations at lower levels to evidence the differences between snow seasons analyzed.

This study considers the snow season from November to May (NDJFMAM), and we will refer to it as “season” hereinafter. On the other hand we will use the terms “winter” and “spring” in order to make reference to the climatological winter (DJF) and spring (MAM), and “winter season” when we add March to winter (DJFM).

3. RESULTS AND DISCUSSION

3.1 Temperatures

An atmospheric temperature analysis is essential to understanding the evolution of the climate in the high mountain. Obviously the precipitation type depends on temperature. In addition, it determines the formation and persistence of snow cover throughout the season. In this work we use the average monthly and seasonal temperature.

As shown in Figure 2 and Figure 3, the 2011/2012 season, in general, was warmer than normal in Góriz except in February and April, showing great contrasts. On the other hand, the 2012/2013 season exhibits a clear cold anomaly, especially due to very cold February, March and May. In fact, the 2011/2012 season would be classified as warm (with 5 months very warm), while the 2012/2013 season would be classified as very cold. If we analyze the winter season, the 2011/2012 was normal (due to February) and the 2012/2013 was very cold.

Regarding the thermal behavior of the other high mountain stations, it followed a similar pattern, being the 2012/2013 season colder than the previous one. However, a smaller difference between seasons was found towards the east of our study area.

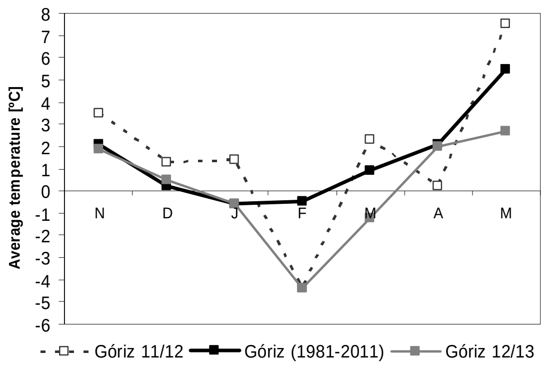

Figure 2. Average monthly temperature during the season in Góriz station.

3.2 Precipitations

As we can see in Figure 4, total precipitation in mm accumulated in 2011/2012 and 2012/2013 seasons was very similar in high mountain stations with the exception of Góriz. According to this reference series, 2011/2012 precipitation was 9% lower than the climatic median and 2012/2013 precipitation was 23% higher (Figure 5). Thus, the

Weather Station	Season	N	D	J	F	M	A	M	Season	Winter	Spring
Respomuso	2011/2012	2.9	0.5	0.5	-5.4	2.0	-0.3	7.3	1.1	-1.5	3.0
	2012/2013	1.3	-2.4	-0.7	-5.4	-1.6	-0.7	2.0	-1.1	-2.8	-0.1
Góriz	2011/2012	3.5	1.3	1.4	-4.4	2.3	0.2	7.5	1.7	-0.6	3.3
	Average (*)	2.1	0.2	-0.6	-0.5	0.9	2.1	5.5	1.4	-0.3	2.8
	2012/2013	1.9	0.5	-0.6	-4.4	-1.2	2.0	2.7	0.1	-1.5	1.2
Ángel Orús	2011/2012	2.7	0.5	1.0	-3.7	2.2	-0.2	7.1	1.4	-0.7	3.0
	2012/2013	1.9	-0.2	0.2	-4	-1.3	2.2	2.6	0.2	-1.3	1.2
La Renclusa	2011/2012	1.7	-0.9	-1.6	-6.2	0.2	-0.5	6.8	-0.1	-2.9	2.2
	2012/2013	1.1	-1.9	-2.1	-5.4	-1.2	1.0	2.0	-0.9	-3.1	0.6

Figure 3. Average monthly, winter, spring and seasonal temperature in ℃ in 2011/2012 and 2012/2013 seasons at the high mountain stations. (*) Reference period (1981-2011).

Weather Station	Season	N	D	J	F	M	A	M	Total	Winter	Spring
Respomuso	2011/2012	230	87	31	65	33	337	122	904	182	492
	2012/2013	71	110	131	140	172	69	187	880	381	428
Góriz	2011/2012	333	38	21	40	52	247	116	848	99	416
	Median (*)	187	103	92	73	80	124	155	930	298	392
	2012/2013	173	115	182	105	307	101	163	1146	402	571
Ángel Orús	2011/2012	251	12	17	20	100	210	97	707	49	407
	2012/2013	139	76	158	39	164	50	158	784	273	372
La Renclusa	2011/2012	289	112	68	30	71	240	73	883	211	383
	2012/2013	168	53	130	55	138	109	193	845	238	440

Figure 4. Total monthly, winter, spring and seasonal precipitation in mm in 2011/2012 and 2012/2013 seasons at the high mountain stations. (*) Reference period (1981-2011).

2011/2012 season would be classified as dry and 2012/2013 season as wet. If we do a monthly analysis, there was a general lack of precipitation in the 2011/2012 season, with the exception of November and April. In fact, both 2011/2012 winter and winter season were extremely dry (the driest of the series). On the other hand, the 2012/2013 winter was wet and the winter season very wet.

As regards as precipitation in the four high mountain stations, significant differences appear in winter and winter season depending on their location. In stations more exposed to south flows, much higher precipitation was observed in the 2012/2013 winter compared with 2011/2012 (approximately six and four times higher in Ángel Orús and Góriz respectively), while this increase was lower in areas more exposed to north flows (Respomuso and specially La Renclusa, with only 12% higher precipitation in 2012/2013). If winter season is considered, again La Renclusa exhibits the lowest difference, with only 34% higher precipitation in 2012/2013. In spring the differences between the seasons are generally lower, and no differences were found with respect to the location of the stations.

The fact that temperature was clearly lower and precipitation clearly higher in the 2012/2013 winter season explains to a great extent the higher snowfall registered in this season. Figure 6 summarizes nivological data. Regarding Number of Snow Days (NSD), there was a general increase in the 2012/2013 season with respect to the previous one, but a different behaviour related to stations location was observed. Consistent with the thermal behaviour difference observed, the NSD difference between seasons decreases gradually towards the east in the high

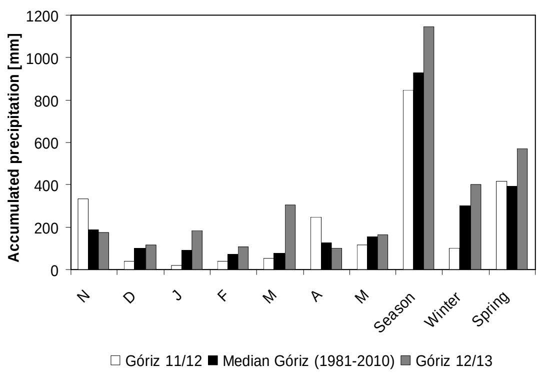

Figure 5. Total monthly, winter, spring and seasonal precipitation in Góriz.

	Season	Season Snowall (cm)	Winter Snowfall (cm)	NSD (%)	Snowfall days >10 cm
Respomuso	2011/2012	513	208	30	10
	2012/2013	941	648	52	24
Góriz	2011/2012	334	65	18	12
	2012/2013	697	349	32	26
Ángel Orús	2011/2012	259	33	17	7
	2012/2013	512	241	28	20
La Renclusa	2011/2012	530	216	32	10
	2012/2013	764	404	37	25

Figure 6. Nivological data in the high altitude stations in 2011/2012 and 2012/2013 seasons.

mountain. In addition, a higher number of significant snowfalls (>10 cm) were observed in all high altitude stations during the 2012/2013 season.

In terms of total snowfall, it was generally two times higher in the 2012/2013 season than in 2011/2012, with the exception of La Renclusa where it was 70% higher approximately. In the same way that happened with precipitation, in stations more exposed to south flows, much higher snowfall was observed in 2012/2013 winter compared with 2011/2012 (approximately seven and five times higher in Ángel Orús and Góriz respectively), while this increase was lower in areas more exposed to north flows (approximately three and two times higher in Respomuso and La Renclusa respectively). If winter season is considered, the increase in Respomuso and Ángel Orús is similar, but La Renclusa keeps on showing the least increase, with 50% higher snowfall in 2012/2013.

3.3 Snowpack

An indicator of snowy behaviour is the number of days with snow on the ground (Figure 7). In this section, we decided to incorporate lower altitude stations in order to represent better all the altitudinal ranges. Above 2000 m.a.s.l. in areas more exposed to north flows about 90% of snow cover days exists independently of the weather variables. In this case the persistence of snow on the ground is not a good indicator to show the different behaviour of the two seasons. However, at stations more exposed to south flows and at lower altitudes, very sensitive to the different pluviometric and especially thermal behaviour between the two winter seasons, the percentage of days with presence of snow was much higher in the 2012/2013 season. It is necessary to emphasize the great difference between the lowest and similar altitude stations. Linza, much more exposed to north flows, show a lower interseasonal variability in snow persistence than Pineta which it is more exposed to south flows.

Figure 8 shows the temporal evolution of snowpack depth in both seasons. Obviously, higher contrasts are located in lower altitude stations. Although the 2011/2012 season started early it is not possible to identify a consolidated snowpack for the whole season in the study area except in areas more exposed to north flows above 2000 m.a.s.l. Only in April there was a period of remarkable snowfalls that brings a significant increase in the snowpack depth which begins to decline after the first week of May due to the typical spring melting. However, the 2012/2013 season, despite starting a little later than the 2011/2012, was characterized by a well-consolidated snowpack since early December in all stations. The significant and continuous snowfalls that occurred from mid-January to mid-February meant a considerable increase in the snowpack depth, reaching maximum values of the season. From that date, low

Weather Station	Season	Persistence (% of days)
Respomuso	2011/2012	88
	2012/2013	93
Góriz	2011/2012	40
	2012/2013	91
Ángel Orús	2011/2012	34
	2012/2013	75
La Renclusa	2011/2012	94
	2012/2013	91
Estós	2011/2012	37
	2012/2013	73
Casa de Piedra	2011/2012	25
	2012/2013	73
Linza	2011/2012	29
	2012/2013	67
Pineta	2011/2012	9
	2012/2013	55

Figure 7. Percentage of days with presence of snow on the ground.

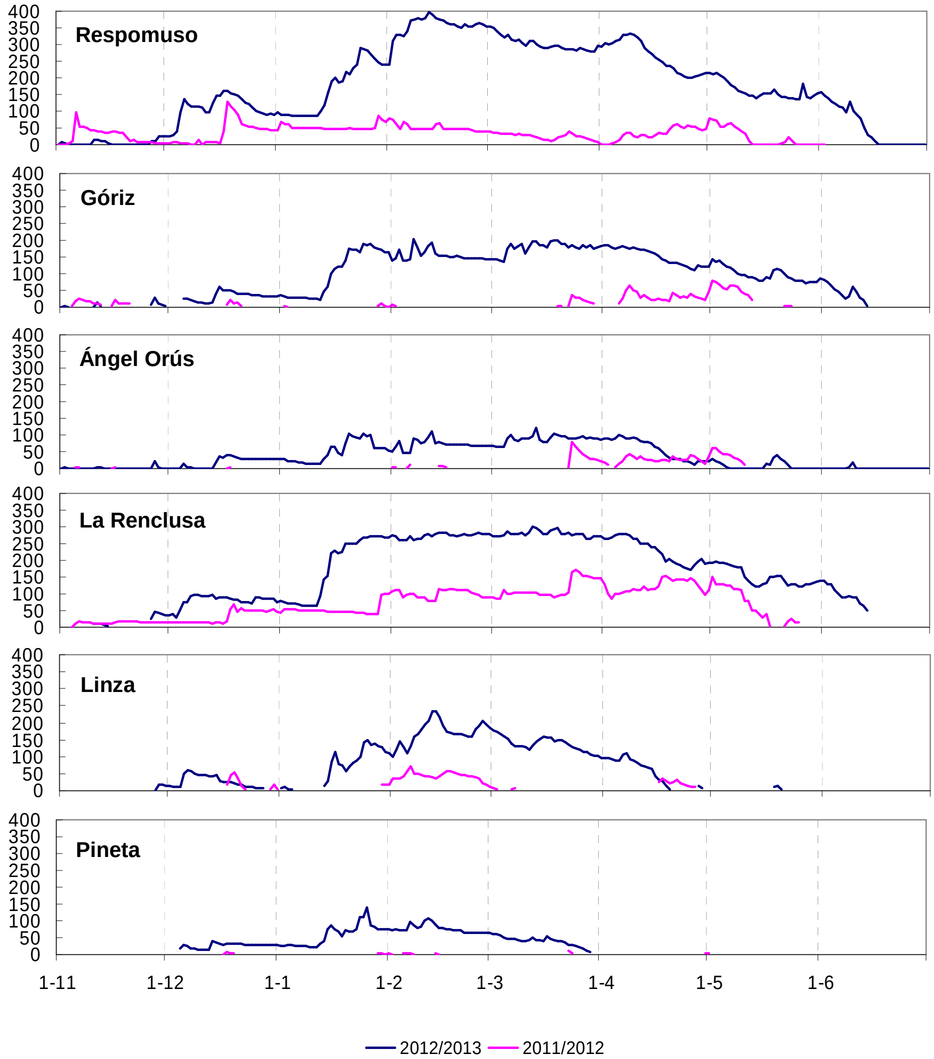

Figure 8. Temporal evolution of the snowpack depth (cm) in the different stations. The first four figures correspond to the high altitude stations and the last two figures to the lowest altitude stations.

temperatures and persistent snowfalls favoured the persistence of snowpack, even until the early summer in the high altitude stations.

4.3 *Relationship with Atmospheric circulation: NAO*

Previous research has identified the NAO as one of the dominant atmospheric patterns on the temporal evolution of precipitation and temperature in the Mediterranean area (e.g. Hurrell and van Loon, 1997; Trigo et al., 2002). Regarding the Spanish and Andorran Pyrenees, some authors have worked with the relationship between NAO and snow avalanche activity (e.g. García-Sellés et al., 2010), heavy snowfall days (e.g. Esteban et al., 2005), interannual variability of snowpack (e.g. Revuelto et al., 2012) or weather variables (e.g. López-Moreno et al., 2011; Peña et al., 2006).

This section tries to demonstrate the correlation between the average winter season NAO and both the average winter season temperature and total winter season precipitation in our reference series of Góriz. We used the Spearman correlation coefficient because it is robust and resistant, good for series which are not normal distributed such as the precipitation one (Wilks, 2006). We also checked whether the statistic was statistically significant, choosing a significance level of 5 % (α = 0.05). We decided to use these four months because winter is the season in which the effect of the NAO is greater and winter season, together with April, is the period in which more snow is usually accumulated in the study area. We used the monthly NAO index of the National

Oceanic and Atmospheric Administration (NOAA) to calculate the average index for the winter season. Finally, we try to compare temperature and precipitation anomalies in Góriz with the NAO index in 2011/2012 and 2012/2013 winter seasons, and analyze if there is a similar behaviour in the rest of stations.

Figure 9 already shows a clear correlation between the temperature and the NAO in Góriz from the winter season 1981/1982 to the winter season 2010/2011. As we can see in figure 10, the correlation is positive and statistically significant, with a Spearman correlation coefficient greater than 0.6. Most of the winters with NAO values below zero exhibit a negative anomaly in their winter season temperature, while all those ones with NAO values exceeding 0.5 exhibit a positive anomaly.

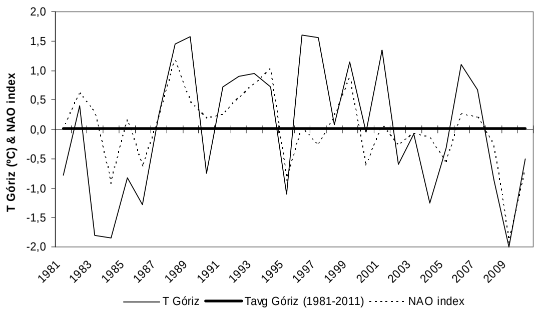

Figure 9. Temporal evolution of the winter season NAO and the winter season temperature in Góriz station in the 1981-2011 period. The thick line represents the average temperature for all the period.

Regarding precipitation, again the temporal evolution plot (figure 11) gives evidence of a correlation between the winter precipitation and the winter NAO. However, in this case the correlation is negative and statistically significant, with a Spearman correlation coefficient slightly lower than in the temperature case. All the winters with NAO values below -0.5 exhibit a positive or a slight negative anomaly in their precipitation (with respect to the median in this case), while those ones with NAO values exceeding 0.5 exhibit a negative or a slight positive anomaly.

	T Góriz	Pcp Góriz
ρ	**0.607**	**-0.525**
p_value	0.001 (< α)	0.005 (< α)

Figure 10. Spearman correlation coefficient between the winter season NAO and the winter season temperature and precipitation in Góriz station in the 1981-2011 period.

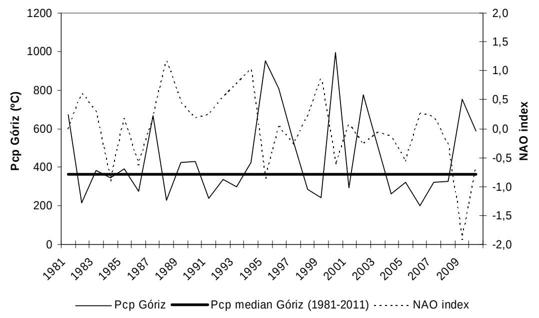

Figure 11. Temporal evolution of the winter season NAO and the winter season precipitation in Góriz station in the 1981-2011 period. The thick line represents the average temperature for all the period.

These results seem to be logical, since the Góriz refuge, despite being very close to the watershed, is more affected by the moisture advected by regional southwest and west flows, which show the best correlation in Central Spanish Pyrenees with the NAO (López-Moreno and Vicente-Serrano, 2007). The reason, as it was mentioned before, rely on the large and continous orographic barrier of the Góriz's watershed (3000 m mountains), which makes that Atlantic humid northwest and north flows arrive with less humidity in the refuge area.

Focussing on the last two winter seasons in Góriz, the winter season NAO was very high in 2011/2012 (Figure 12), the third highest of the series. Following the correlation observed during the 1981-2011 period, the 2011/2012 winter season was extremely dry. However, although there was a slight positive temperature anomaly, the thermal behaviour of the 2011/2012 winter season was normal, mainly due to a very cold february, in which there were frequent cold and dry advections from the northeast regional flows that show poor correlation with the NAO (López-Moreno and Vicente-Serrano, 2007). On the other hand, the winter season NAO index in 2012/2013 was very low, the fourth lowest since 1981. Following the correlation observed during the 1981-2011 period, a very cold and very wet winter was observed in Góriz.

As we analyzed before in 3.1. and 3.2. sections, great differences in temperature, precipitation and snowfall were found between the last two winter seasons in all the stations, which are summarized in Figure 13. We found interesting results related to a great extent to the different sign of the winter season NAO. Firstly, the 2012/2013 winter season was colder and wetter than the previous one in all stations. Secondly, the temperature difference

Season	T (ºC)	Anomaly T (ºC)	Pcp (mm)	Anomaly Pcp (mm)	Behaviour	NAO index
2011/2012	0.2	0.2	152	-214	**Normal / Extremely dry**	**1.02**
2012/2013	-1.4	-1.4	710	344	**Very cold / Very wet**	**-0.77**

Figure 12. Averages and anomalies in winter season temperature and precipitation in Góriz, and winter season NAO indexes in 2011/2012 and 2012/2013.

between the two winter seasons decreases from west to east in the high mountain stations. Finally, precipitation is much higher in 2012/2013 winter season in all stations except in La Renclusa. This refuge is more exposed to regional north flow (which possess poor correlation with the NAO; López-Moreno and Vicente-Serrano, 2007) than to regional south flows (especially southwest flow are well correlated with the NAO), and therefore the influence of the NAO is lower. Something similar probably happens in the case of Linza refuge, which exhibits very different results than Pineta.

Station	T diff. (ºC)	Pcp diff. (mm) (%)	Snowfall diff. (cm) (%)
Respomuso	-1.9	338 (257)	547 (331)
Góriz	-1.6	558 (468)	438 (534)
Ángel Orús	-1.3	288 (293)	262 (330)
Renclusa	-0.5	94 (134)	169 (150)
Estós	-1.7	307 (312)	234 (231)
Casa de Piedra	-1.5	669 (426)	644 (738)
Linza	-1.0	612 (215)	366 (276)
Pineta	-1.1	693 (555)	297 (843)

Figure 13. Differences in temperature, precipitation and snowfall of the winter season 2012/2013 compared with the winter season 2011/2012. 100 % would be the amount registered in 2011/2012.

4 CONCLUSIONS

We have analyzed the different behaviour of snowpack between 2011/2012 and 2012/2013 seasons. It has been shown that the period which has made the difference was the winter season, since all the stations registered lower temperature, higher precipitation, and consequently higher snowfall, in the 2012/2013 winter season. In fact, in our reference series of Góriz the 2011/2012 winter season was normal and extremely dry, while the 2012/2013 winter season was very cold and very wet.

Regarding the winter season NAO, a statistically significant correlation, positive with temperature and negative with precipitation, have been demonstrated in the reference series of Góriz during the 1981-2011. The climate weather values of the last two winter seasons seem to follow this correlation. Furthermore, a good relationship between the winter season NAO and the characteristics of the last two winter seasons has been detected in the rest of stations, with lower influence in those ones more exposed to north flows.

However, a more complete study taking into account other teleconnection patterns and trying to obtain more reference series in AEMET nivometeorological stations will be necessary in the future.

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