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Spatial and temporal variability of winter snow and precipitation days in the western and central Spanish Pyrenees

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ABSTRACT: In this study we analysed the spatial distribution of the long-term average and interannual variability of the number of snow days (NSD) and the number of precipitation days (NPD) in winter (DJFM) in the Spanish Pyrenees, using data from 38 meteorological stations for the period 1981–2010. The interannual variability of the NSD and the NPD in winter was related to the frequency of weather types over the Iberian Peninsula. Data from six stations were also used to analyse a longer time period (1961–2013) to confirm the consistency of the results obtained during the main study period (1980–2010).

The results indicated that the NPD is only influenced by the distance to sea whereas the NSD is determined by elevation and distance to the sea. A high frequency of west (W), northwest (NW) and cyclonic (C) weather systems led to a high NPD in winter across the entire study area, whereas the frequency of north (N) weather types was only correlated with the NPD at the most westerly stations. For the NSD there was a gradient from the Western Pyrenees to eastern areas, mainly explained by the frequency of N weather types in the former area, and high frequencies of NW and W weather types associated with the latter. For most stations there was no significant trend found in the NPD or the NSD for the 1981–2010 period. However, a slight decrease was found for stations strongly correlated with NW weather types, and a slight increase was found for stations strongly correlated with the C weather type, which was related to a decreasing (increasing) frequency of NW (C) weather types during the same period. Analysis of the 1961–2013 and 1971–2000 time slices using a smaller subset of stations revealed a similar relationship between weather types and the NSD. This indicates that the 1981–2010 period is sufficiently representative to describe the relationship of the NSD and the NPD to weather type frequency. However, the study period chosen can markedly influence the trends observed, as the results showed a statistically significant decrease in the NSD for the 1971–2000 period, but no significant trends for the 1961–2013 and 1980–2010 periods.

KEY WORDS   snow days; winter precipitation days; weather types; temporal trends; Pyrenees; Spain

1. Introduction

Study of the spatial and temporal variability of the snowpack is of great interest because this variability controls the ecology and hydrological response of mountainous areas and cold regions (Barnett *et al.*, 2005; Mellander *et al.*, 2007; Jonas *et al.*, 2008a, 2008b), and affects economic activities including winter tourism, hydropower generation and water supply for agriculture (Beniston, 2003; Barnett *et al.*, 2005; Lasanta *et al.*, 2007; Uhlmann *et al.*, 2009). Furthermore, the interannual variability of snowpack and snow cover is directly related to temperature and precipitation in the preceding months, and is thus a useful indicator of climate variability and change in areas where climate data of good quality are generally lacking (Wash, 1995; Nesje and Dahl, 2000; Carrivick and Brewer, 2004).

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The snowpack plays a major role in the hydrology of the Pyrenees region (López-Moreno and García-Ruiz, 2004), and determines the potential of Pyrenean reservoirs to supply water during the dry season (López-Moreno *et al.*, 2008a). A decrease in snow accumulation occurred in this region during the second half of the 20th century (López-Moreno, 2005), and this has been partially attributed to changes in the frequency of weather types over the Iberian Peninsula (López-Moreno and Vicente-Serrano, 2007). However, the effects of these changes can be spatially variable in the Iberian Peninsula, because interactions between topography and exposure to different air masses lead to marked differences in the response of neighbouring areas to synoptic or hemispheric circulation patterns (Corte-Real *et al.*, 1998; Goodess and Jones, 2002; Esteban *et al.*, 2005; Vicente-Serrano and López-Moreno, 2006). Snowpack simulations according to climate projections from various regional climate models (RCMs) indicate an acceleration of the observed trends during coming decades, which will have profound effects on areas at low elevations (López-Moreno *et al.*,

2008b; López-Moreno *et al.*, 2009; Maris *et al.*, 2009). Despite numerous studies of changes in the snowpack in the Pyrenees and other Spanish mountains, studies of other snow-related variables including the number of days on which snowfall is recorded have not been undertaken. The number of snow days (NSD) is an important indicator of climate variability and change, because it provides detailed information concerning the number of precipitation days (NPD) when the temperature is below freezing. The annual NSD and variability also has important implications for management of the Pyrenees area, especially in populated areas where the NSD is on average very low and winter preparedness is limited. Snowfall in inhabited areas disrupts transport, increases the number of traffic accidents and injured pedestrians and affects the normal functioning of infrastructure (Vajda *et al.*, 2012). From an economic point of view the proper maintenance of roads and communication services is expensive, and can affect the income from ski resorts and tourism in mountain areas, with potentially negative effects on local economies (●Pons *et al.*, 2003; Scott and McBoyle, 2007; Gonseth, 2013).

The relatively few studies considering snow days is explained by the poor reliability of the long-term data series for this variable, as it is dependent on direct intra-day observations of precipitation falling as snow. In ●western United States (Knowles *et al.*, 2006) a shift from snowfall total precipitation to rainfall total precipitation detected during the 1949–2005 period attributed to a temperature increase on wet days and which mainly affected the sites, which had mean temperatures warm enough that moderate warming was sufficient to impact the precipitation form.

In the Swiss Alps a decrease in the number of snowfalls has been detected, and associated with precipitation falling as rain rather than snow. This trend is more significant at mid- and low elevations, although the magnitude of change is very dependent on the study period (Laternser and Schneebeli, 2003; Serquet *et al.*, 2011).A recently published article (Scherrer *et al.*, 2013) shows large decadal variability with phases of low and high values for the snowfall events.

Regarding the French Pyrenees, Maris *et al.* (2009) due to the lack of a sufficient amount of directly observed long-term snow data had to use climate reanalysis for the 1958–2008 periods using the SAFRAN and CROCUS models. This work shows that precipitation trends are not significant, making it hard to detect clear tendencies in French Pyrenees.

Pons *et al.* (2010) used data from 34 stations to analyse the evolution of snow days throughout northern Spain during the period 1957–2002. The NSD showed a negative trend from the mid-1970s, as a consequence of increasing temperature and decreasing precipitation at some stations at high elevation. However, this study only included three stations in the western Pyrenees, and the most important mountain sector of Spain in terms of snow accumulation and duration was not included.

In this study we analysed the spatial variability and trends in the NSD and the NPD in the western and central Spanish Pyrenees. We used a newly created dataset derived from a dense network of meteorological stations where these indices have been regularly recorded. The objectives of the study were: (1) to identify the main geographical factors leading to the spatial variability of the NSD and the NPD; (2) to analyse the interannual evolution and observed trends in the NSD and the NPD and (3) to relate variability to atmospheric circulation at the regional scale, using an objective weather type classification.

2. The study area

The study area encompasses the central and western Spanish Pyrenees (Figure 1). The eastern Spanish Pyrenees was excluded because it has very few stations providing long climatic series. The elevation in this region increases from west to east, with maximum peak heights ranging from 300 m to slightly more than 3000 m a.s.l. However, the stations used in this study are generally located in towns and villages, and all are located at less than 1500 m a.s.l.

Precipitation varies following north–south and west–east gradients, based on the elevation and the transition from Atlantic to Mediterranean climate characteristics (García--Ruiz *et al.*, 2001). The average elevation gradually increases from west to east. The topographic heterogeneity of the region partially explains the large spatial variability of annual precipitation. Stations at mid-elevations (approximately 800 m a.s.l.) in western areas receive more precipitation in winter than stations at the same elevation in central areas.

Temperatures are determined by elevation. Del Barrio *et al.* (1990) estimated a gradient of 0.68 °C 100 m^{-1} of altitudinal increase. From November to April the 0 °C isotherm is at approximately 1600–1700 m a.s.l. (García-Ruiz *et al.*, 1986), representing the level above which accumulated snow remains for extended periods. Our study focused on areas below 1500 m a.s.l., where the population density is greater, and consequently where snowfall causes more problems. Although snowfall in these areas has effects at higher elevations, these were not considered in the study because long-term climate series for these elevations are not available.

3. Data and methods

3.1. Climate data

Data on snow and precipitation in the area have been recorded at meteorological stations managed by the Spanish Meteorological State Agency (AEMET). The main study period was from 1981 to 2010, and was restricted to the winter period from December to March (DJFM). This period was selected because: (1) it is the last 30 years climate standard reference period of time (normal period) as recommended by the World Meteorological Organization (WMO, 1989) and (2) it contains the largest number of stations having long climate series. However, for six stations it was possible to obtain series covering the period 1961–2013, enabling analysis of the study results in a wider temporal context.
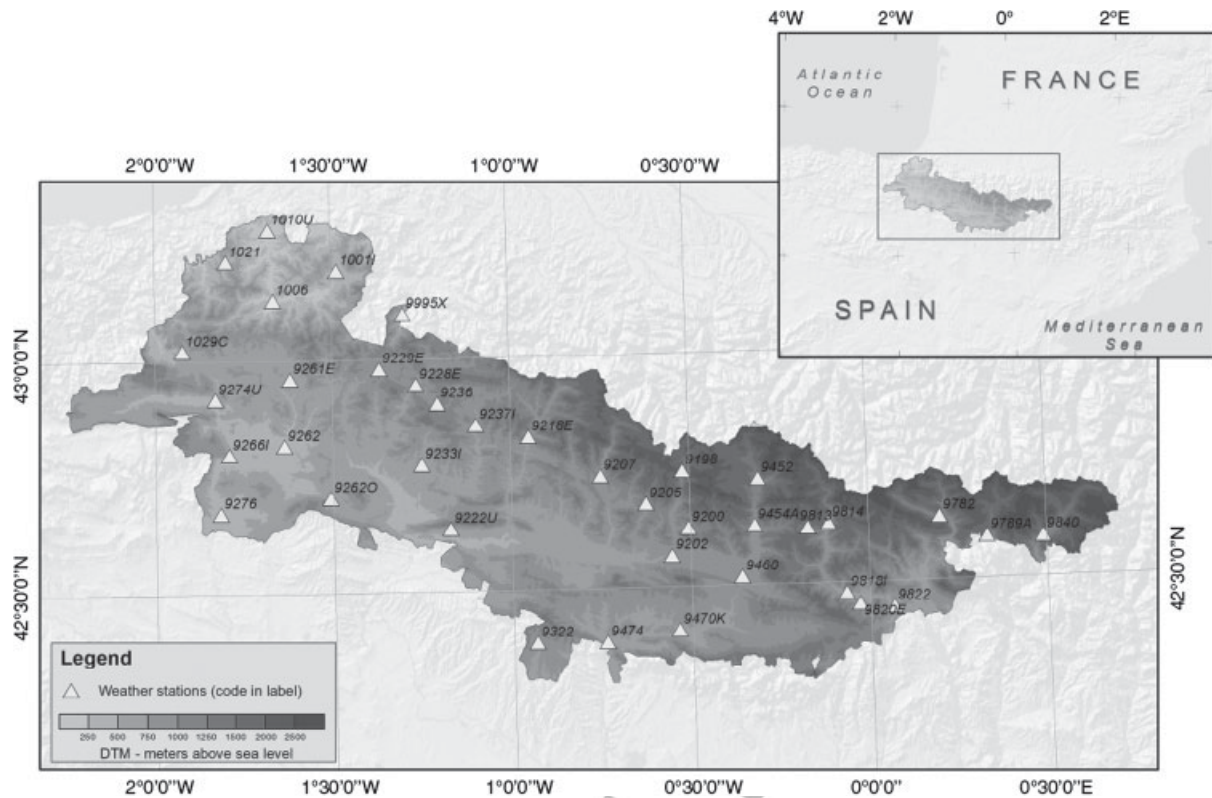
Figure 1. Study area and location of weather stations. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

A snowfall event is recorded on the database if it occurred within a 24-h period, day or night, (from 06:00 UTC to 06:00 UTC), even if it does not cover the ground. Precipitation events were based on a threshold of 0.1 mm total precipitation. This threshold was used in order to account for weak snowfalls with low precipitation rates (<1 mm) and recorded also on the database as snow day. The precipitation database did not show too many cases below 1 mm, around 5% on average. If liquid and solid forms of precipitation have been reported on the station on the same day, both events are recorded on the database as a precipitation and snow day. The database did not include the amount of precipitation associated with each event. All these data were manually checked and corrected by AEMET staff prior to be recorded in the AEMET database. The original database contained data from more than 100 stations. The criteria for selection were the data quality (previous knowledge of climate series and observer) and that the data availability exceeded 90% for each series for the study period. Missing data of a particular station were filled by means of linear regression using neighbouring stations that exhibited a high coefficient of correlation ($r > 0.9$) with the candidate series and located <10 km distant and at a comparable elevation (within 200 m). In many cases the hand written manuscript as recorded by the observer was verified on AEMET climatological archive and some mistakes were found and corrected. Using this procedure, the percentage of missing data that were completed was less than 7% of the all database.

The final database contained 38 complete series covering the entire study period (Table 1). The elevation of the selected stations ranged from 45 to 1422 m a.s.l., and the stations were representative of low- and mid-elevation sectors of the western and central Spanish Pyrenees. The distances of the stations from the Atlantic Ocean ranged from 17 to 207 km.

To separate the effects of station elevation and distance to the ocean, which was necessary to explain the spatial variability of the long-term average and the interannual variability of the distribution of snowfall and precipitation days, we used stepwise regression models to facilitate identification of the significant predictors. The beta coefficients of the regressions were used to compare the relative weight of the predictors in explaining the long-term average and the interannual variability of snowfall and precipitation days.

3.2. Weather type classification

Daily weather types over the Iberian Peninsula were obtained using the objective weather typing system of Jenkinson and Collison (1977), which is based on the Lamb types Lamb and Peppler (1987) ● The method requires information on the daily sea level pressure at the 16 points (at 5° resolution) that comprise the Iberian Peninsula (López-Moreno and Vicente-Serrano, 2007). Sea level pressure data were obtained from the ●NCEP database (http://www.esrl.noaa.gov/). The Jenkinson and Collison method (described by Jones *et al.*, 1993) has been successfully used for daily weather type classification in the

Table 1. List of analysed stations and their elevation, distance to the sea and mean NSD and NPD during winter (DEFM) for the 1981–2010 period.

Station code	Name	Elevation (m)	Distance to sea (km)	NSD	NPD
9236	Abaurrea Alta	1047	73	20.7	54.4
9205	Aisa De Jaca	1040	125	13.4	38.4
9228E	Arive	700	66	9.9	52.0
1001I	Arizcun De Baztan	257	36	4.4	56.9
1021	Articutza	305	17	6.0	64.9
1029C	Azpiroz-Casa Cia	545	32	9.5	64.4
9200	Bescos De Garcipollera	920	136	11.1	37.6
9322	Biel	760	132	6.7	34.7
9454A	Biescas (Central II)	855	148	10.4	37.9
9822	Boltaña	643	186	3.5	24.8
9198	Canfranc Los Ara/Ones	1160	127	19.6	45.6
9452	El Pueyo De Jaca	1091	143	15.5	34.8
9233I	Eparoz	605	82	5.7	42.9
9840	Eriste (Central)	1100	207	10.6	26.0
9237I	Esparza De Salazar	687	83	16.8	51.1
9229E	Espinal-Auzperri	870	59	15.8	52.5
9789A	Gistain	1422	196	17.5	31.1
9207	Hecho	855	112	13.0	42.5
9274U	Irurzun	455	45	8.8	50.0
9202	Jaca	800	137	9.9	38.0
9470 K	Javierrelatre	709	151	7.3	29.5
9474	La Peña (Embalse)	589	142	3.0	28.1
9222U	Leyre Monasterio	756	98	10.0	41.8
9813	Linas De Broto	1333	159	9.6	22.6
9262O	Monreal	545	77	6.4	43.6
9261E	Olague	545	48	9.1	51.0
9266I	Otazu	387	59	3.5	39.7
9262	Pamplona Observatorio	442	61	7.7	50.9
9782	Pineta (Presa)	1150	184	10.9	30.5
9276	Puente La Reina	346	72	4.6	42.9
9460	Sabiñanigo	790	153	6.4	32.0
9820E	San Felices	812	179	5.9	22.5
9818I	Santa Olaria De Ara	740	175	5.9	26.9
1006	Santesteban	131	31	3.1	58.4
9814	Torla	1053	162	12.4	32.7
9218E	Urzainqui	717	94	12.3	52.5
9995X	Valcarlos	320	54	5.0	61.5
1010U	Vera De Bidasoa	45	17	2.5	62.7

Iberian Peninsula, with particularly good results during winter (Goodess and Palutikof, 1998; Spellman 2000). The method discriminates each day among 26 possible weather types: anticyclonic (A); cyclonic (C); eight directional weather types (N, NE, E, SE, S, SW, W and NW); and types that are hybrids of cyclonic, anticyclonic and directional types (CN, CNE, CE, CSE, CS, CSW, CW, CNW, AN, ANE, AE, ASE, AS, ASW, AW and ANW). To simplify the interpretation of the results, the 26 weather types were aggregated into 10 types by elimination of the hybrid types, following the approach of Jones *et al.* (1993) and Trigo and Da Camara (2000). When a hybrid type was encountered, a value of 0.5 was added to the frequency series for the relevant cyclonic (C) or anticyclonic (A) type, and 0.5 was added to the corresponding directional type (N: north, NE: northeast, E: east, SE: southeast, S: south, SW: southwest, W: west and NW: northwest). The number of days for each synoptic situation observed during winter (December to March) was considered in analysing the relationships among weather types and the snowfall series.

4. Results

4.1. Snowfall and precipitation days climatology

Table 1 shows that the long-term average NPD ranged from 22 to 65, while for the NSD the range was 3–4 days per year to almost 21 days. Figure 2 shows the contour plot relating the long-term average and the coefficient of variation of precipitation days to elevation and distance to the sea, and Table 2 shows the correlation coefficients of the NSD and the NPD with elevation and distance to the sea. The NPD decreased with distance to the Atlantic Ocean ($r = -0.91$) and decreased with increasing elevation ($r = -0.61$); elevation increases towards the east, whereas precipitation gradually decreases in this direction. Stations close to the sea (<50 km), and thus at lower elevation, accounted for the greatest NPD, and this factor had a clear influence on the correlation results. It is noteworthy that the stations close to the sea accounted for at least twice as many precipitation days relative to those 100 km or more from the sea. The interannual variability was greater at
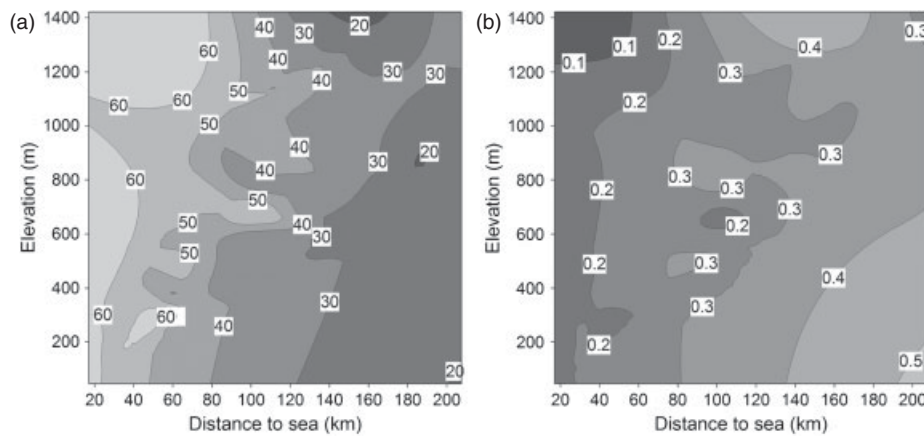
Figure 2. (a) Relationship of the NPD (long-term average) to elevation (m) and distance to the Atlantic Ocean (km). (b) Relationship of the interannual coefficient of variation for the NPD to elevation (m) and distance to the Atlantic Ocean (km).

Table 2. Pearson's correlation coefficients and explanatory variables and coefficients resulting from stepwise multiple linear regressions.

	Correlations		Multiple linear regression					
			Standardized coefficients				Beta coefficients	
	E	D	Constant	E	D	R^2	E	D
NSD	0.72**	0.21	2.49	0.02	−0.67	0.79	1.31	−0.77
NSD – coefficient of variation	−0.84**	−0.48**	0.96	−0.01	0.01	0.76	−1.12	0.36
NPD	−0.61**	−0.91**	64.3	x	−0.20	0.84	x	−0.91
NPD – coefficient of variation	0.56**	0.85**	0.18	x	0.01	0.73	x	0.85

E • denotes elevation (m) and D denotes distance to the sea (km). *$\alpha < 0.05$; **$\alpha < 0.01$.

high elevation stations ($r = 0.56$) and those more distant from the ocean ($r = -0.85$). Figure 3 shows a contour plot relating the long-term average and the coefficient of variation for the NSD with elevation and distance to the sea. The trend in the NSD was opposite to that for the NPD, as it decreased at lower elevation ($r = 0.72$) and increased slightly, but not significantly, with greater distance from the ocean ($r = 0.21$). This was the result of multicolinearity between elevation and distance to the ocean. Despite this strong linear relationship, some stations located at moderate elevations (approximately 1000 m a.s.l.) had the highest NSD in the study area; these stations are located relatively close to the Atlantic Ocean. The interannual variability was greater for the NSD than the NPD, and it decreased linearly with elevation ($r = -0.84$) and distance to the ocean ($r = -0.48$).

To assess the effect of elevation and distance to the ocean in explaining the NPD and the NSD, we conducted four separate stepwise multiple linear regressions using the long-term average and the coefficients of variation for the NPD and the NSD as dependent variables, and elevation and distance to the sea as independent variables. The coefficients, explained variance and beta coefficients obtained for each regression are shown in Table 2.

A high percentage of the variance in the long-term average (79%) and the coefficient of variation (76%) for the NPD was explained by distance to the Atlantic Ocean. Elevation was not included in the model, which confirmed the occurrence of multicolinearity between elevation and distance to the ocean. However, models explaining the spatial distribution of the long-term average and interannual variability of the NSD include both elevation and distance to the ocean as predictors; 79 and 76% of the variance shown by the spatial distribution of NSD and its interannual variability was explained by the models. If distance to ocean was not included in the models, the explained variance was 53 and 70% for the average and coefficient of variation of the NSD, respectively. The beta coefficients also indicated the importance of the contribution of distance to the ocean (−0.77 and 0.36) and elevation (1.31 and −1.12) as predictors in the two models explaining the mean and interannual variability of the NSD.

4.2. Relationship between weather types and climate variables

Table 3 shows the frequency of occurrence of the various weather types during winter (December to March) over the Iberian Peninsula. During the study period the anticyclone weather type dominated, with a frequency of approximately 35% (Table 3). The cyclonic weather type occurred on 11% of the days. The NW and N weather types had frequencies of 8–10%, and the remaining types (NE, SE, S, SW, W and E) ranged from 4 to <8%.

Figure 4 shows that in any winter the occurrence of certain weather types exerted a clear influence on the NPD and the NSD, and the NPD/NSD ratio. Figure 4(a) shows
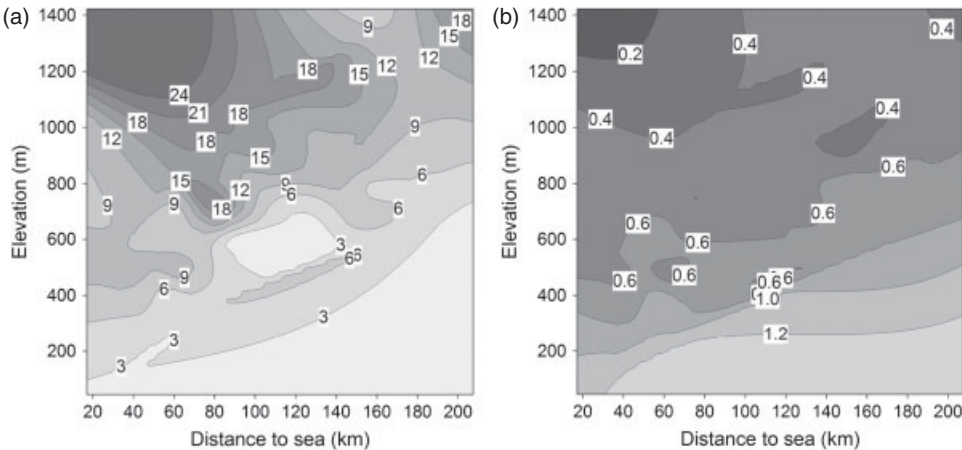
Figure 3. (a) Relationship of the NSD (long-term average) to elevation (m) and distance to the Atlantic Ocean (km). (b) Relationship of the interannual coefficient of variation for the NSD to elevation (m) and distance to the Atlantic Ocean (km).

Table 3. Frequency (%) of the various weather types in winter (DJFM).

A	C	N	NE	E	SE	S	SW	W	NW
33.85	11.26	9.21	6.03	7.28	6.91	4.43	6.14	6.59	8.30
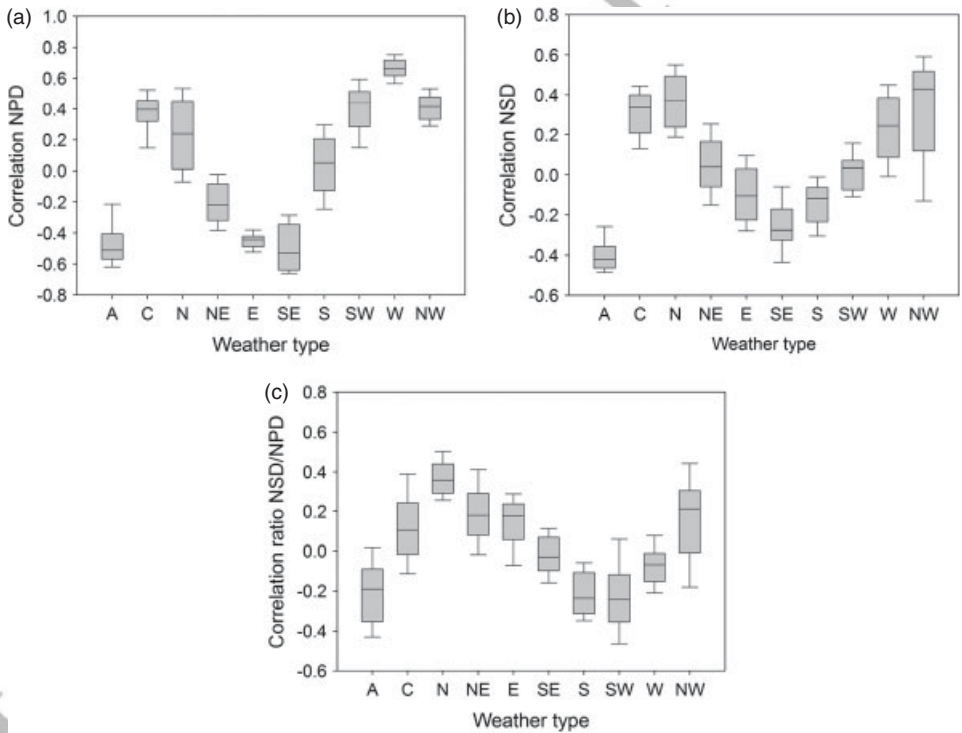
Figure 4. Box-plots showing the variability among stations in the correlation between the interannual occurrence of weather types and the NPD (a), the NSD (b) and the NSD/NPD ratio (c). The central line indicates the mean, the boxes are the 75th and 25th percentiles, and the bars indicate the 90th and 10th percentiles.

that a high frequency of C, N, SW, W and NW weather types led to a high NPD. The W and NW weather types were characterized by a low dispersion in the correlation values, indicating that these atmospheric patterns produce precipitation over the entire study area. The C type showed rather low dispersion but clearly included outliers, while the SW and N types showed higher dispersion values, indicating that they had contrasting effects on the NPD across the study area. Winters with more frequent A, E and SE types were characterized by a lower NPD.

Figure 4(b) shows that the frequency of C, N, W and NW weather types was positively correlated with the NSD. However, the high dispersion evident in the box-plots suggests that the frequency of each weather type had
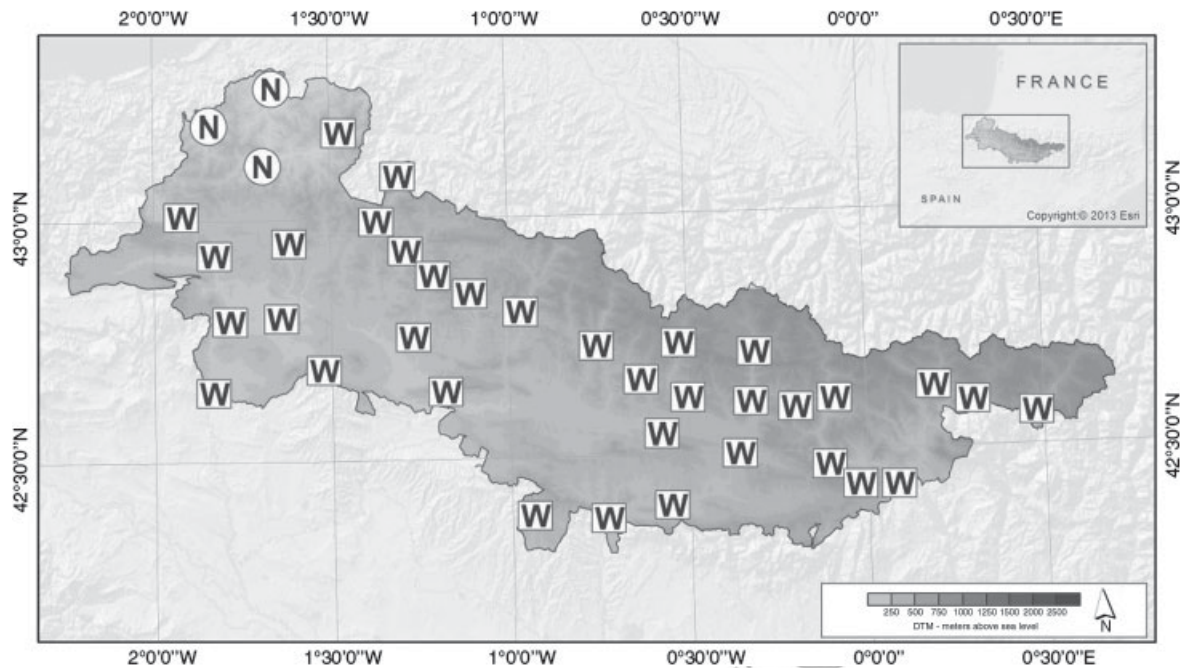
Figure 5. Weather types showing the greatest positive correlation with the NPD per station. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

different effects at the stations in the study area. The SW weather type did not correlate with the NSD, in clear contrast to its correlation with the NPD. A high frequency of anticyclonic days led to a low NSD. Weather types with an easterly component (E and SE) were associated with a low NSD, but this was not as obvious as the very negative coefficients for the NPD.

The NSD/NPD ratio (Figure 4(c)) clearly increased with northerly flows, and was greater in association with flows from the north and the east (N, NE, E and NW). The N weather type exhibited lower dispersion among stations, while the NW type showed very large dispersion.

Figure 5 shows the weather type most strongly correlated with the NPD at each station. All these correlations were >0.5 and statistically significant ($\alpha < 0.01$). The NDP at most of the stations was most highly correlated with the annual frequency of W weather types; for three stations, located in the northwest of the study area, the correlation with N weather types was higher.

Figure 6 shows the relationships between the value of correlation of the NPD and the frequency of W, N, NW and C types with elevation and distance to the sea. The latter two did not show the strongest correlation at any station (Figure 5), but had a strongly positive correlation with the NPD (Figure 4). Table 4 shows that the N and NW weather types were negatively correlated with distance to the sea, because stations far from the sea are more blocked from humid flows. In the case of the N types the fit was almost linear ($r = -0.91$), and was very strong in the case of NW types ($r = -0.68$). Similar correlations were evident in relation to elevation, because it increases with distance from the sea. Considering the values from which significant correlations ($\alpha < 0.05$) were obtained (dashed line in Figure 6) it can be inferred that N weather types

mainly caused precipitation at stations <120 km from the sea. The W and C weather types were positively correlated ($r = 0.55$) and ($r = 0.74$), respectively, with distance to the sea because these flows were able to affect all stations, including those at distance from the sea; the Pearson's correlation coefficients were therefore high and positive for all stations. However, the NPD at stations furthest from the sea show clearly a higher positive response to these types being also positively correlated with elevation, because elevation increases far from sea on eastward direction they were positively correlated with elevation.

Figure 7 shows the relationships between the NSD and the weather type most strongly correlated for each station. All correlations were significant ($\alpha < 0.05$) for all stations, and strongest for stations at higher elevations (Figure 8).

The NSD in the western area, and at mid-to-high elevation stations, was mainly associated with the N weather type. In the central part of the Pyrenees the strongest correlation was with the NW weather type. The W weather type was strongly correlated at only two stations (Gistain and Torla), which are located at the highest elevations and are in a valley open to westerly influences. The C weather type was characteristic of stations at low elevations near the sea, or at stations distant from both the sea and the highest areas of the Pyrenees.

To investigate the relationship between NSD and weather type we compared the Pearson's correlation coefficients for each relevant weather type (N, NW, W and C) producing snowfall with elevation and distance to the sea. Figure 8 and Table 4 show that the NW and W weather types showed a positive and strong correlation ($r = 0.86$) and ($r = 0.81$), respectively, with elevation being the main factor determining whether snowfall was likely to occur. Consequently, stations at high elevations that
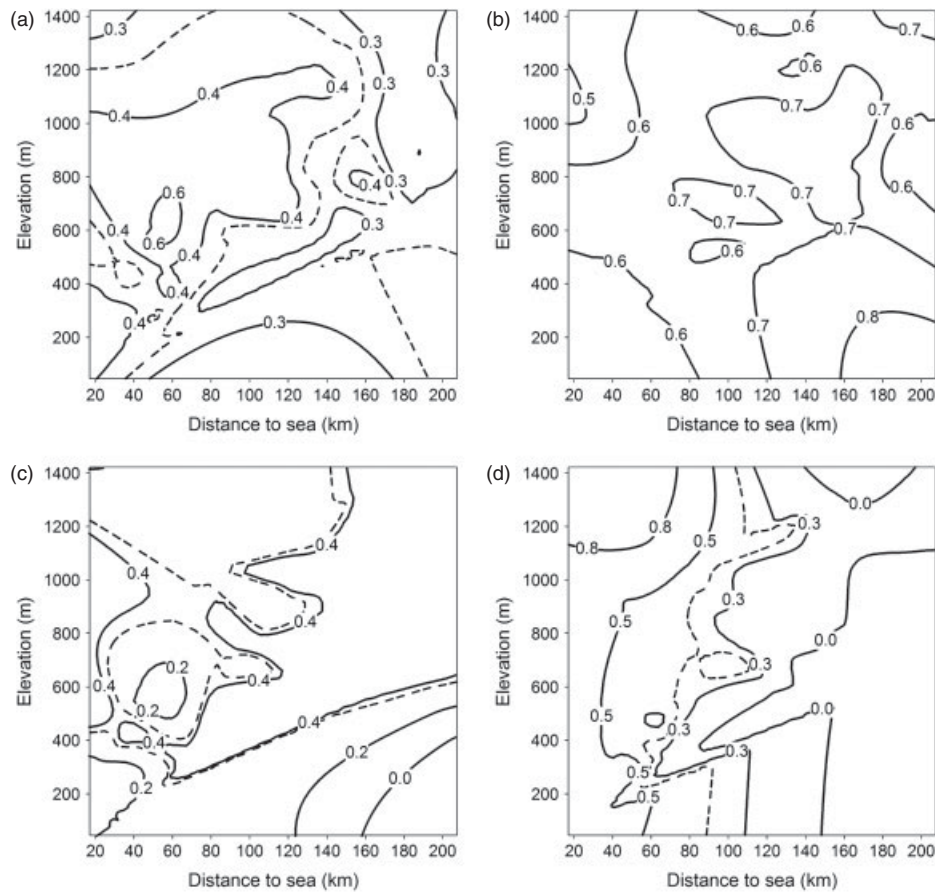
Figure 6. Relationships between the value of the correlations of the NPD and the frequency of weather types with elevation and the distance to the sea. The dashed lines show the limit of significance of the Pearson's correlation coefficient ($\alpha < 0.05$). Weather types: (a) NW, (b) W, (c) C and (d) N.

Table 4. Pearson's correlation coefficients between weather types (N, NW, W, C) and the NSD and the NPD with elevation and distance to the sea.

Weather type	Snow days (NSD)		Precipitation days (NPD)	
	Elevation (m)	Distance to sea (km)	Elevation (m)	Distance to sea (km)
NW	0.86**	0.72**	−0.37*	−0.68**
W	0.81**	0.74**	0.58**	0.55**
C	−0.38*	−0.30	0.51**	0.74**
N	−0.01	−0.31	−0.55**	−0.91**

*$\alpha < 0.05$; **$\alpha < 0.01$.

were strongly correlated with NW weather type were also strongly correlated with the W weather type. The difference was because westerly flows (W) are associated with higher temperatures than the northwesterly flows (NW). For the NW type, 22 stations had correlation coefficients >0.5, while for the W type this occurred for only three stations. The C weather type had a significant negative correlation ($r = -0.38$) with elevation, and also a negative (but not significant) correlation with distance to the sea. In addition, these stations receive less snow on average than the others, and although significant the correlation coefficients were very low. For the N weather type, ten stations in the western area had correlations >0.5. This weather type was associated with cold air over the entire area and did not appear to be related to elevation, and

distance to the sea was the major factor related to snowfall occurrence. For the weather types NW and W for which significant correlations ($\alpha < 0.05$) were found (dashed line in Figure 8), the rain–snow line was estimated to be at approximately 700 m for the NW type, while for the W type it was estimated to be at approximately 1100 m for the stations <40 km from the sea. This decreased eastward to approximately 800 m for the stations 100–180 km from the sea.

4.3. Trends in the NSD and the NDP: relationship with variability in atmospheric circulation

To detect significant trends, temporal series were tested against a linear time evolution (1981–2010) using the nonparametric Spearman's rank correlation statistic test.
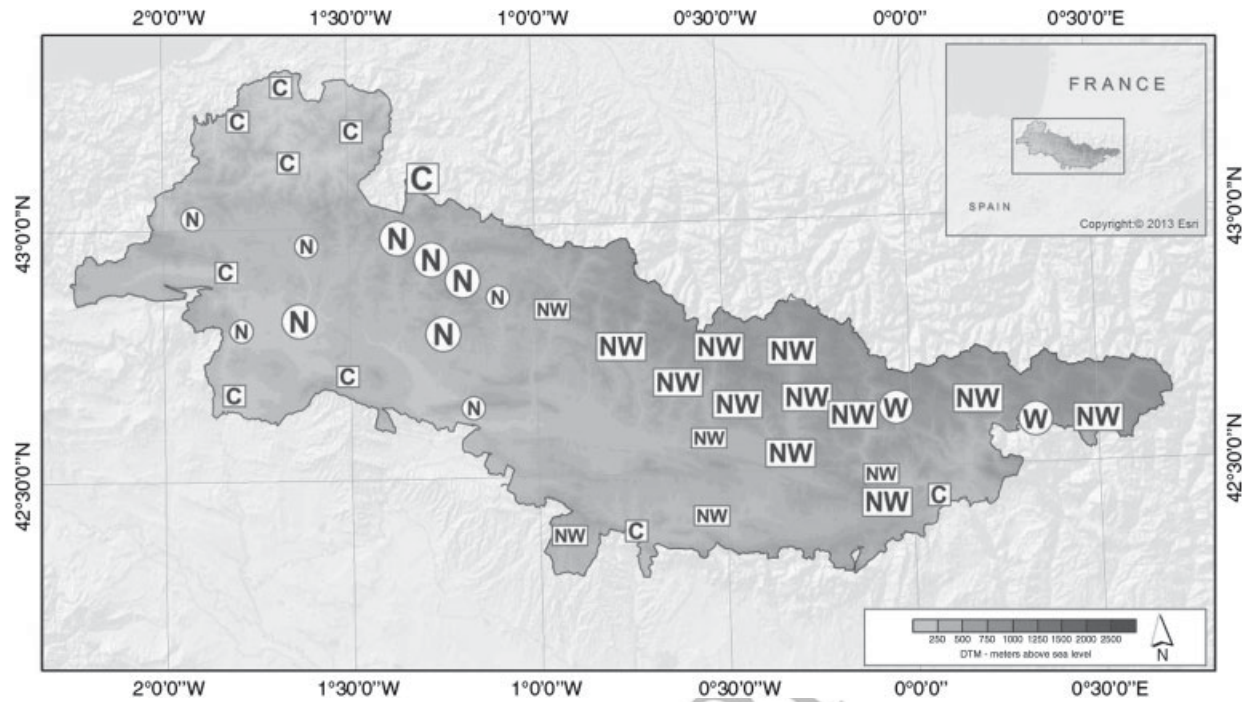
Figure 7. Weather types having the strongest positive correlation with the NSD per station. The size of the symbol indicates whether the correlation coefficient was greater or less than 0.5. This figure is available in colour online at wileyonlinelibrary.com/journal/joc
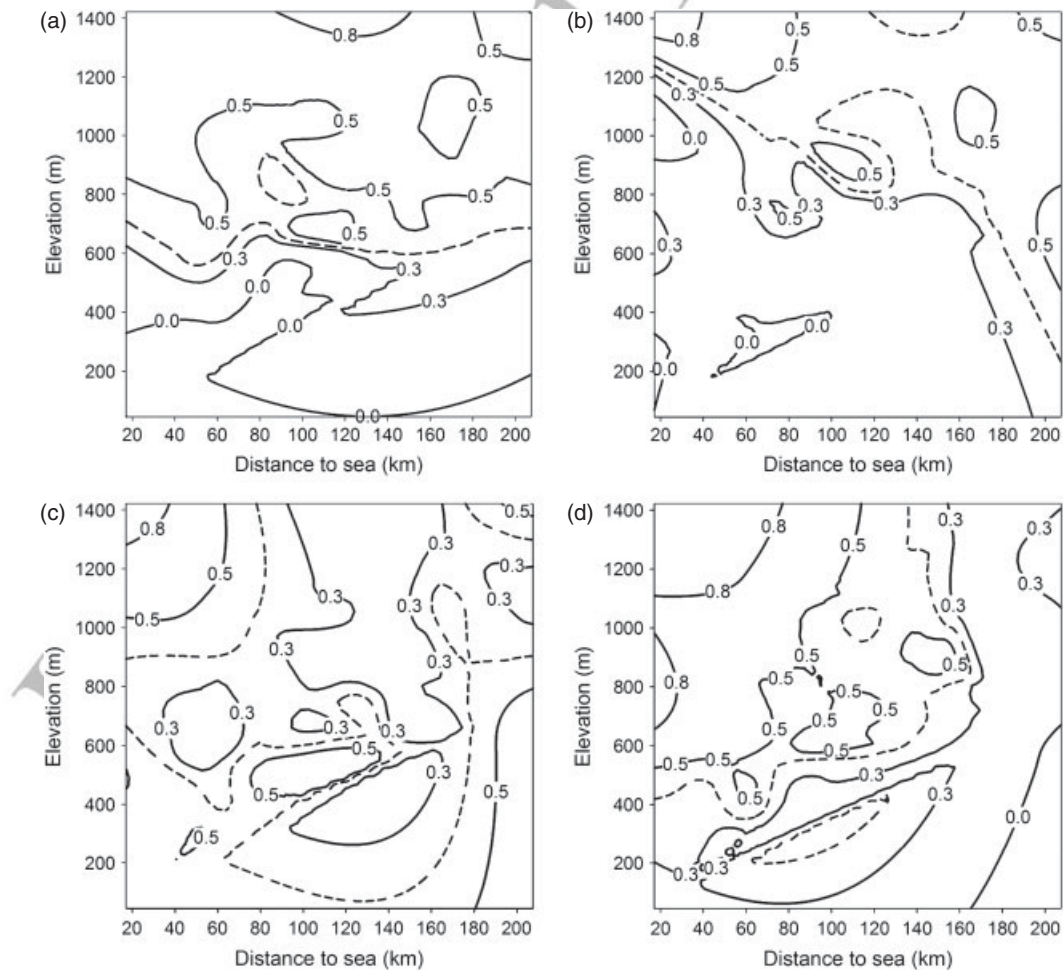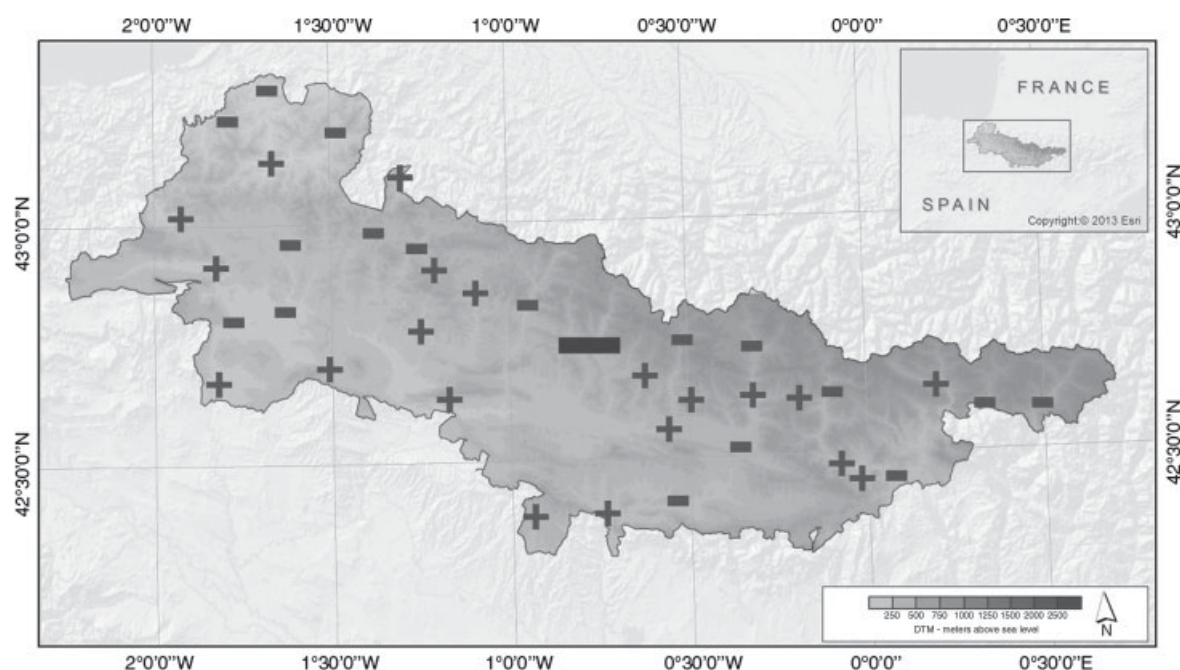
Figure 8. Relationship of the value of the correlation for the NSD and weather type with elevation and distance to the sea. The dashed line shows the limit of significance of the Pearson's correlation coefficient ($\alpha < 0.05$). Weather types: (a) NW, (b) W, (c) C and (d) N.

Figure 9. Trends in the NPD in the study area: (+) positive, (−) negative. The large size of the symbol indicates a significant correlation ($\alpha < 0.05$). This figure is available in colour online at wileyonlinelibrary.com/journal/joc
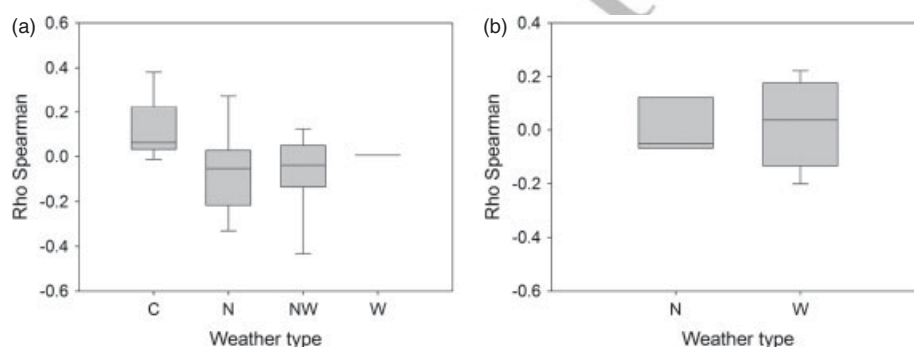
Figure 10. Box-plots for the weather types that were most strongly correlated at each station. (a) NSD and (b) NPD.

Figure 9 shows the spatial distribution of the trends in the NPD in the study area. Only one station showed a significant negative trend during the study period. Figure 10 shows the variability in the temporal trends amongst those stations for which the NPD was more influenced by N and W weather types, and the NSD was more influenced by C, N, NW and W weather types (Figures 5 and 7). This shows that there was no evident associated between the temporal trends in the NPD and the dominant weather type.

Figure 11 shows the spatial pattern of trends in the temporal evolution of the NSD at the study stations. As for the NPD, most of the trends were not statistically significant, with only two stations showing a significant negative trend, and one showing a significant increase in the frequency of the NSD. Figure 10 shows the variability in the temporal trends among those stations more influenced by the C, N, NW and W weather types (Figure 7).

In general, those stations having the strongest correlation between the NSD and W weather types showed positive coefficients for their temporal trends, whereas the stations more related to the N and NW weather types had negative coefficients for their temporal evolution. These results are consistent with the decrease and increase in the NW and C weather types, respectively (Table 5), which indicates the temporal trend in the frequency of the various weather types during winter for the main study period (1981–2010) and the two other time slices considered (1961–2013 and 1971–2000). Table 5 shows the absence of significant trends for all weather types except for the NE type, which increased during the 1981–2010 period. Several statistically significant changes were evident during the period 1971–2000, including a significant increase in the A and E weather types, a significant decrease in the SW and W types and a decrease in N, NW and C types.

4.4. The 1961–2013 period: an exploratory analysis of variability in the NSD

To obtain a broader view of the temporal evolution of the NSD we analysed the six available series encompassing the 1961–2013 period. These stations were sufficiently
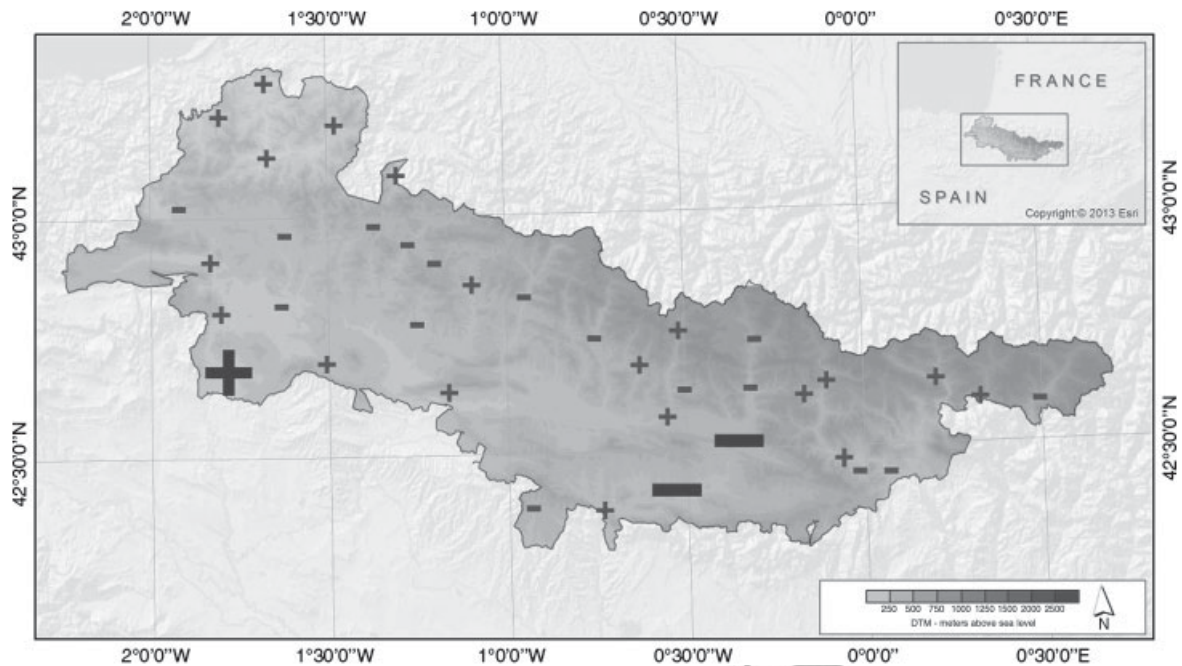
Figure 11. Trends in the NSD per station: (+) positive, (−) negative. The large size of the symbol indicates a significant correlation ($\alpha < 0.05$). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table 5. Temporal trends (Spearman's rho statistic) in the frequency of various weather types for different time periods.

Weather type	1961–2013	1971–2000	1981–2010
A	0.13	0.46*	−0.05
C	−0.23	−0.13	0.13
N	−0.10	−0.24	0.10
NE	−0.02	0.16	0.42*
E	0.11	0.37*	0.11
SE	0.14	0.21	0.09
S	−0.14	−0.11	−0.08
SW	−0.37*	−0.38*	−0.31
W	−0.13	−0.37*	−0.12
NW	−0.15	−0.26	−0.25

*$\alpha < 0.05$.

representative because, with the exception of the Santesteban station, they receive a significant amount of snowfall. They are also far enough from each other that they are very likely to be affected by different weather types. Figure 12 shows the temporal evolution of the NSD at these six stations. A high NSD was evident at the beginning of 1960s, followed by a decrease at the end of that decade. The 1970s and early 1980s were characterized by a high NSD, but the end of the 1980s and most of the 1990s were characterized by a lack of snow. The most recent period has been very variable, with winters having abundant snowfall alternating with others having very few snowfall days.

Table 6 shows the correlation between stations and weather types for the 1961–2013 period. The A weather type was negatively and significantly correlated at the six stations. The strongest correlations (0.01 level of statistical significance) were found for the W and NW weather types at all stations except Santesteban. The same level of

statistical significance was found for the N weather type for the Abaurrea, Canfranc and Bescos stations, whereas for the most easterly stations (Torla and Pineta) there was a strong correlation with the frequency of the C weather type. Similar relationships between the NSD and weather types were also found for this set of stations for the 1981–2010 period (Table 6); similar values for Pearson's correlation coefficients were maintained between both periods. As occurred for the period 1971–2000, the western stations were mainly affected by the N and NW weather types, and the stations to the east were mainly affected by the NW, W and C weather types. This demonstrates that the results for the period 1981–2010 can be used to accurately reflect the behaviour and variability of snowfall in the study area.

Table 7 shows temporal trends in the NSD for different periods of time: the entire period available (1961–2013); the 1971–2000 period, which is still used as the standard reference period for comparison in many countries; and the most recent period (1981–2010), which was studied in more depth in this study.

Temporal series were tested against a linear time evolution (1981–2010) using the nonparametric Spearman's rank correlation statistic test. Table 7 also reports about the slope of the linear regression in order to illustrate the magnitude of the change.

Depending on the time slice considered, different results were obtained. Thus, the NSD showed a negative trend at all stations during the 1971–2000 period, and it was significant at four stations. After linear fitting the decrease in the NSD per decade at the Pineta station was up to 4.9 days decade^{-1}. This was consistent with the significant increase in A weather type and the decrease in N, NW, W and C weather types, as shown in Table 5. However, no
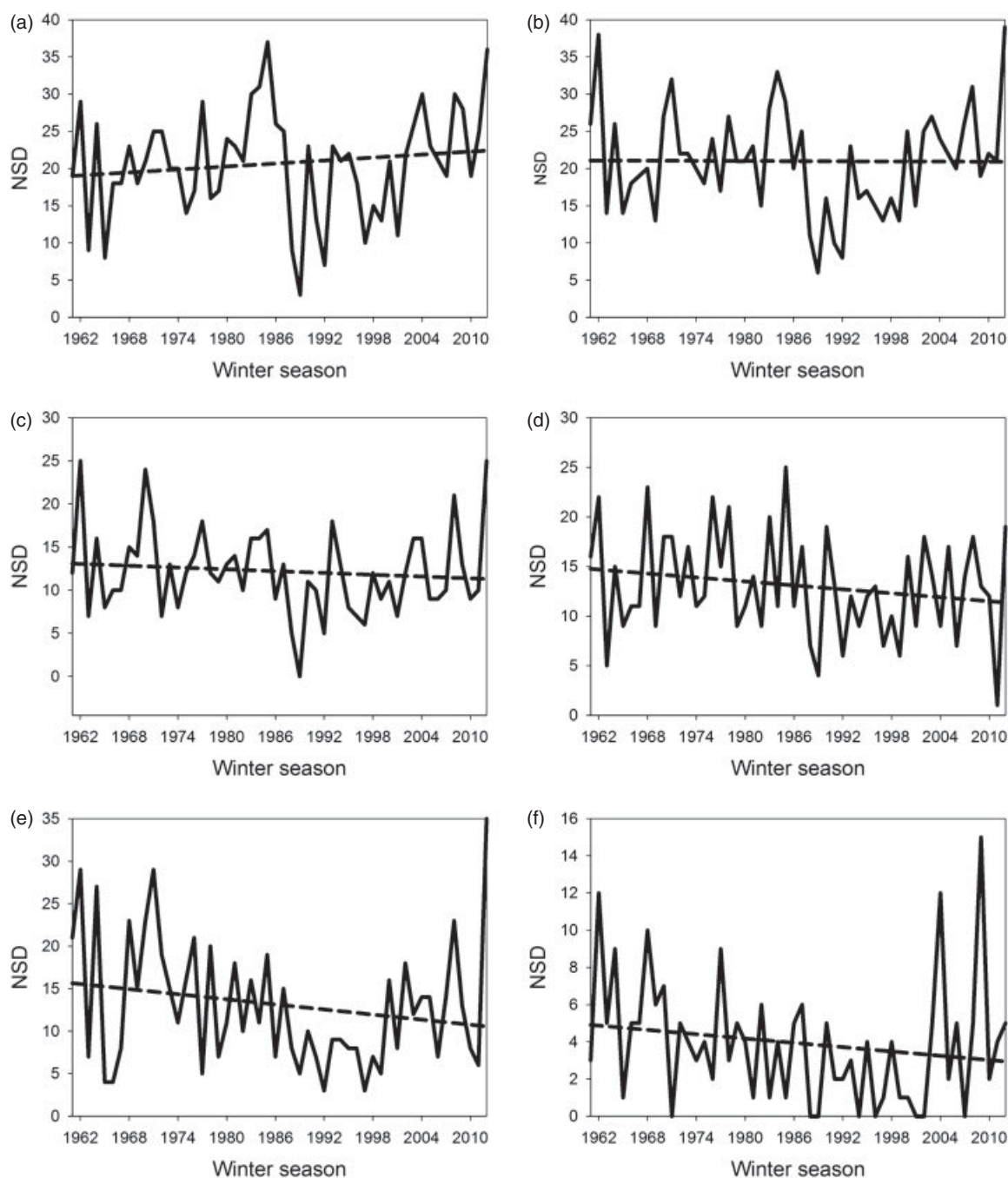
Figure 12. Temporal evolution of the NSD (1961–2013) for selected stations having long climate series and a linear fit to the data. (a) Abaurrea, (b) Canfranc, (c) Bescos, (d) Torla, (e) Pineta and (f) Santesteban.

Table 6. Correlation between stations and weather types for the 1961–2013 (1981–2010) period.

Station	A	C	N	W	NW
Abaurrea	−0.38* (−0.45**)	0.23 (0.38*)	0.47** (0.59**)	0.27* (0.40*)	0.40** (0.47**)
Canfranc	−0.43* (−0.37*)	0.25 (0.17)	0.30* (0.46*)	0.37** (0.36*)	0.50** (0.59**)
Bescos	−0.29* (−0.32)	0.19 (0.09)	0.35* (0.52**)	0.31* (0.24)	0.51** (0.54**)
Torla	−0.49** (−0.47**)	0.35** (0.37*)	0.14 (0.19)	0.57** (0.53**)	0.48** (0.43*)
Pineta	−0.46** (−0.46**)	0.34* (0.26)	0.19 (0.21)	0.37** (0.44*)	0.38** (0.55**)
Santesteban	−0.42** (−0.43*)	0.28* (0.41*)	0.18 (0.23)	0.06 (0.07)	−0.18 (−0.14)

*$\alpha < 0.05$; **$\alpha < 0.01$.

Table 7. Temporal trends (Spearman's rho statistic; ρ) and slope (s) in the NSD decade^{-1} (linear fit) of the frequencies of NSD for three time periods.

Station	1971–2000		1981–2010		1961–2013	
	ρ	s	ρ	s	ρ	s
Abaurrea	−0.34	−3.0	−0.05	−0.13	0.14	0.6
Canfranc	−0.56**	−4.2	0.10	0.88	−0.01	0.0
Bescos	−0.36*	−1.7	−0.01	0.32	−0.12	−0.3
Torla	−0.43*	−2.5	0.00	0.30	−0.14	−0.6
Pineta	−0.67**	−4.9	0.05	0.64	−0.20	−0.3
Santesteban	−0.28	−0.8	0.08	1.11	−0.24	−0.9

*$\alpha < 0.05$; **$\alpha < 0.01$.

statistically significant trends were found for any station for the 1981–2010 and 1961–2013 time slices.

5. Discussion

In this study we analysed the distribution and temporal evolution of the NSD and the NPD in the Spanish Pyrenees in relation to the frequency of various weather types affecting the Iberian Peninsula.

A key aspect of this work was the creation of a robust database to serve as a starting point for our analyses. Thus, the data for the period 1981–2010 from a dense network of 38 weather stations were analysed, and for 6 stations the data from a longer time slice (1961–2013) were analysed.

The spatial distribution and the temporal evolution of the long-term average NPD and NSD were affected by the interaction between atmospheric flows and the orography of the study area. The average NSD on some locations reaches the 20% of the total winter days (DJFM). They also show a great interannual variability depending on the prevailing weather types. In some years, snow days in several stations exceeded the 40% of winter days.

The spatial distribution of the average NPD was predominantly affected by distance to the Atlantic Ocean. However, as the occurrence of snow from precipitation is mostly influenced by elevation, this suggests that temperature is a major factor explaining the number of days of snowfall in this region. However, distance to the ocean markedly influenced the altitudinal gradient of the NSD. Thus, mid-elevation stations (700–1000 m a.s.l.) in the western area had a similar NSD to stations located above 1000 m a.s.l. in the eastern area. These results suggest that in the west of the study area the greatest influence on the NPD is the frequency of N weather types, which are associated with cold temperatures. In contrast, the W weather type (associated with milder temperature) has a greater influence to the east, where elevations are higher, which may explain why more snowfall days occur at lower elevations. The interannual variability of the NPD increased with elevation and distance to the sea, whereas the NSD was much less variable from 1 year to the next at the highest elevation stations.

The NSD and the NDP were highly dependent on the weather type and frequency during winter. In addition, the weather types varied in their effects in different geographical areas, primarily because of factors including the proximity to the Atlantic Ocean, orographic blocking, elevation and the aspect of the stations. Previous studies have reported complex interactions between topography and exposure to different air masses, which have led to marked differences in the response of neighbouring areas to synoptic or hemispheric circulation patterns over the Iberian Peninsula (Corte-Real *et al.*, 1998; Goodess and Jones, 2002; Esteban *et al.*, 2005; Vicente-Serrano and López-Moreno, 2006). The Iberian Peninsula is primarily influenced by two types of hemispheric circulation: subtropical highs and extratropical storm tracks that affect northern Europe. In winter the tracks shifts towards the equator. Therefore, the great sensitivity of the frequency of precipitation and snow days at the regional level in the Iberian Peninsula is likely to be mainly because of variations in the strength and frequency of the synoptic weather types affecting this area. With regard to the NPD, the W and C weather types affected all stations. The NW type mainly affected stations close to sea, whereas the N type exclusively affected (very significantly) the western stations. With regard to the NSD, the central Pyrenees were mainly affected by the W and NW weather types, whereas the N weather type is blocked by the main axis of the mountain range that runs from west to east in this area, and exceeds 3000 m a.s.l. The NW and W types are associated with moist air that is not very cold. The W type is associated with fronts that pass over the entire area, producing precipitation at all stations, and snow at those stations at higher elevations.

This is consistent with several studies reporting that the W and SW types favour the accumulation of snowpack at elevations above 1650 m a.s.l. (Lopez-Moreno and Vicente-Serrano, 2007). The N weather type affects only western and mid-elevation stations, where strong correlations were found. The N flow is associated with less humid and colder air, because part of the flow is continental and passes to the southern side of the Pyrenees; in this area the elevation of the range is 1500–2000 m a.s.l. The C weather type was associated with weaker correlations than the other weather types, and was only correlated with low elevation areas, or with mid-elevation areas far from the sea. These areas are either blocked by the terrain, or very cold air is needed as a prerequisite for snowfall. The classical pattern is the incursion of cold polar air from northern

Russia, and the subsequent passage of a cyclone from the Atlantic Ocean, covering the Iberian Peninsula. The NSD/NPD ratio only increased significantly with northerly flows, which is expected because colder air is present, and was associated with the C weather type at some stations for the reason explained above.

For high elevation stations several weather types (NW, W, N and C) were generally positively correlated with the NSD. This resulted in less variability in the coefficient of variation because it mainly depends on weather types favouring precipitation, whereas for low elevation stations cold air is needed prior to precipitation and these stations are mainly affected by a single weather type (C).

The strength of the correlation between weather type and the NSD clearly increased with elevation for the NW and W types, whereas for the N and C types there were no significant relationships.

There were no significant trends in the NSD or the NPD over the period 1981–2010; years with abundant snowfall days were followed by years having very few snowfall events. However, an increase (not statistically significant) in the NSD was detected for stations mainly affected by the C weather type, and a slight decrease was found for stations mainly affected by the NW type. This was associated with a slight increase in the C weather type and a slight decrease in the NW weather type during the same period.

Using the available set of stations spanning the 1961–2013 period, it was possible to confirm that the correlations between the annual frequency of weather types and the frequency of the NPD and the NSD for the 1981–2010 period are representative of longer time periods. Hence, the 1981–2010 period is sufficiently long to represent the spatial variability of the NPD and the NSD, and their relationships to the frequency of weather types.

In the 1981–2010 period, the anticyclonic weather type was most frequent, with the next most frequent being the N, NW and C types. This observation is consistent with previous studies concerning atmospheric circulation over the Iberian Peninsula in winter (Vicente-Serrano and López-Moreno, 2006; García-Valero *et al.*, 2012). A predominance of these three types is associated with a high frequency of snowfall occurrence.

However, the frequency of winter weather types showed marked decadal variability in the study region. Thus, the selection of the study period could lead to significant differences when temporal trends are inferred, because climate indicators including the NSD are very sensitive to this effect. Thus, for the period 1971–2000 a significant increase in A weather type and a decrease in the N, W, NW and C weather types was found. This change in the frequency of weather types during the 1971–2000 period has been related to a positive trend in the North Atlantic Oscillation (NAO) in the same period (Quadrelli *et al.*, 2001; López-Moreno and Vicente-Serrano, 2007); this caused a decrease in snow accumulation in the central Pyrenees (López-Moreno, 2005) and some sectors of the Alps (Marty, 2008). However, in the last decade the evolution of the NAO has varied markedly, moderating the slope of the increasing long-term trend (Vicente-Serrano *et al.*, 2010). Thus, years with little snow, such as the 2010–2011 or 2011–2012 winter seasons may be followed by high snowfall winters as 2009–20010 and 2012–2013, which should not be considered as extreme but rather as normal within the typical variability observed. The absence of robust temporal trends in the occurrence of snowfall days is noteworthy; however, during the 1961–2013 period a decrease (not statistically significant) in the NSD was detected for stations located on central Pyrenees. The negative trend during the 1971–2000 period is consistent with the only previous study on this topic in Spain (Pons *et al*, 2010).

For the period 1960–2006 the increase in mean winter temperature was moderate low (approximately 0.20°C decade^{-1}), unlike in summer trend when a sharper increase occurred (0.35 °C decade^{-1}). In line with most of the Northern Hemisphere (Swanson and Tsonis, 2009), winter temperature in the study area has often exhibited negative anomalies compared with the last decade (El Kenawy *et al.*, 2012). Thus, the increase (or even decrease) of temperature during the study period has not been sufficient to produce marked shifts in the solid–liquid phase of the precipitation. The forcing mechanisms that can explain the temperature variability are connected to variations in large-scale atmospheric patterns (El Kenawy *et al.*, 2012). Thus, during the last decade the winter NAO has moderated significantly its positive long-term trend, with an increase in the frequency of years with negative phases (Vicente-Serrano *et al.*, 2010), which lead to a higher frequency of weather types associated with high NSD and NPD (NW, W, C, N) in the study area. This result is consistent with the variability of weather types and correlation with NSD and NPD.

During the last decade a slight decrease of winter temperature and a trend reversal on snow indicators such as NSD have been also detected in the Swiss Alps (Scherrer *et al.*, 2013), which suggests the importance of the decadal variability of the climate that often is superimposed to the climate change signal (Díaz *et al.*, 2001; Easterling and Wehner, 2009).

Other studies conducted in other geographic areas or that they not included the last years have reported stronger signal in the increase of the mean winter temperature, and they have shown significant shift on snowfall–total precipitation ratio (Laternser and Schneebeli, 2003; Knowles *et al.*, 2006; Marty, 2008; Serquet *et al.*, 2011).

Finally, this study is consistent with earlier studies such as Maris *et al.* (2009) where precipitation trends are not significant in the French Pyrenees and the negative trend on NSD during the 1971–2000 period in Northern Spain (Pons *et al*, 2010).

6. Conclusions

The numbers of precipitation and snow days are indicators of climate variability very little used. Our results suggests that the spatial distribution and temporal evolution of the NSD and the NPD in the Spanish Pyrenees are intimately

linked to the variability in the frequency of weather types affecting the Iberian Peninsula. In general, years with high frequency of west (W), northwest (NW) and cyclonic (C) weather systems led to a high NPD. For the NSD there was a gradient from the Western Pyrenees to eastern areas, mainly explained by the frequency of N weather types in the former area, and high frequencies of NW and W weather types associated with the latter.

For most stations there was no significant trend found in the NPD or the NSD for the 1981–2010 period. This lack of statistically significant trend is associated to the low increase of winter temperature along the study period, and not clear shifts in the frequency of the weather types, despite clear decadal oscillations. However, the study period chosen can markedly influence the trends observed, as the results showed a statistically significant decrease in the NSD for the 1971–2000 period, but no significant trends for the 1961–2013 and 1980–2010 periods.

This study suggests that improvements in seasonal forecasting of the dominant synoptic patterns could enable advanced warning of the likelihood of winters having an above or below average NSD and NPD.

Further research is also needed to identify the thresholds in temperature increase that could trigger a decline in the NSD in the study area, particularly in the context of available scenarios for winter temperature in the Pyrenees over the coming decades. Moreover, further research on the duration of snow on the ground and the thickness of the snowpack is also of great interest as it can respond to weather types and changing temperatures in a different manner to NSD.

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## USING e-ANNOTATION TOOLS FOR ELECTRONIC PROOF CORRECTION

Required software to e-Annotate PDFs: <u>Adobe Acrobat Professional</u> or <u>Adobe Reader</u> (version 7.0 or above). (Note that this document uses screenshots from <u>Adobe Reader X</u>)
The latest version of Acrobat Reader can be downloaded for free at: <u>http://get.adobe.com/uk/reader/</u>

Once you have Acrobat Reader open on your computer, click on the Comment tab at the right of the toolbar:

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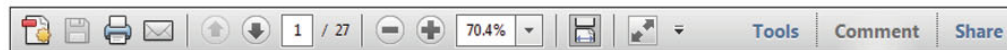
This will open up a panel down the right side of the document. The majority of tools you will use for annotating your proof will be in the Annotations section, pictured opposite. We've picked out some of these tools below:

▾ **Annotations**

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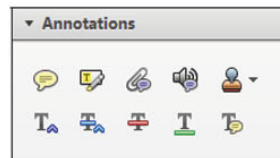
1. Replace (Ins) Tool – for replacing text.

🔁   Strikes a line through text and opens up a text box where replacement text can be entered.

How to use it

- Highlight a word or sentence.
- Click on the Replace (Ins) icon in the Annotations section.
- Type the replacement text into the blue box that appears.

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2. Strikethrough (Del) Tool – for deleting text.

🕂   Strikes a red line through text that is to be deleted.

How to use it

- Highlight a word or sentence.
- Click on the Strikethrough (Del) icon in the Annotations section.

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3. Add note to text Tool – for highlighting a section to be changed to bold or italic.

T₀   Highlights text in yellow and opens up a text box where comments can be entered.

How to use it

- Highlight the relevant section of text.
- Click on the Add note to text icon in the Annotations section.
- Type instruction on what should be changed regarding the text into the yellow box that appears.

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4. Add sticky note Tool – for making notes at specific points in the text.
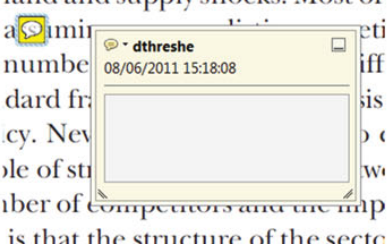
💬   Marks a point in the proof where a comment needs to be highlighted.

How to use it

- Click on the Add sticky note icon in the Annotations section.
- Click at the point in the proof where the comment should be inserted.
- Type the comment into the yellow box that appears.

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## USING e-ANNOTATION TOOLS FOR ELECTRONIC PROOF CORRECTION

5. Attach File Tool – for inserting large amounts of text or replacement figures.

Inserts an icon linking to the attached file in the appropriate pace in the text.

How to use it

- Click on the Attach File icon in the Annotations section.
- Click on the proof to where you'd like the attached file to be linked.
- Select the file to be attached from your computer or network.
- Select the colour and type of icon that will appear in the proof. Click OK.

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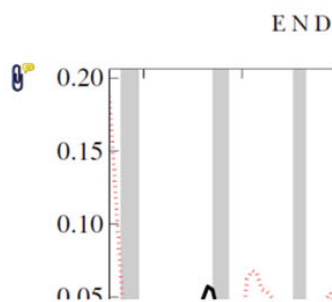
**6. Add stamp Tool – for approving a proof if no corrections are required.**

Inserts a selected stamp onto an appropriate place in the proof.

How to use it

- Click on the Add stamp icon in the Annotations section.
- Select the stamp you want to use. (The Approved stamp is usually available directly in the menu that appears).
- Click on the proof where you'd like the stamp to appear. (Where a proof is to be approved as it is, this would normally be on the first page).

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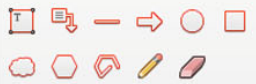
Drawing Markups

7. Drawing Markups Tools – for drawing shapes, lines and freeform annotations on proofs and commenting on these marks.

Allows shapes, lines and freeform annotations to be drawn on proofs and for comment to be made on these marks..

How to use it

- Click on one of the shapes in the Drawing Markups section.
- Click on the proof at the relevant point and draw the selected shape with the cursor.
- To add a comment to the drawn shape, move the cursor over the shape until an arrowhead appears.
- Double click on the shape and type any text in the red box that appears.

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Move to the bottom of the left column of panels.
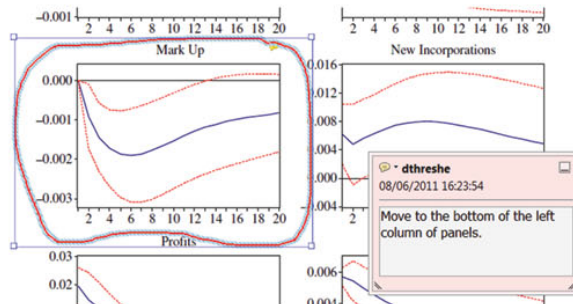
For further information on how to annotate proofs, click on the Help menu to reveal a list of further options:

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