

# 1 **Future Trends of Snowfall Days in Northern Spain from** 2 **ENSEMBLES Regional Climate Projections**

3 **M.R. Pons · S. Herrera · J.M. Gutiérrez**

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6 **Abstract** In a previous study Pons et al. (2010) reported a significant decreasing trend of  
7 snowfall occurrence in the Northern Iberian Peninsula since the mid seventies. The study  
8 was based on observations of annual snowfall frequency (measured as the annual Number  
9 of Snowfall Days NSD) from a network of 33 stations ranging from 60 to 1350 meters. In  
10 the present work we analyze the skill of Regional Climate Models (RCMs) to reproduce this  
11 trend for the period 1961-2000 (using both reanalysis- and historical GCM-driven boundary  
12 conditions) and the trend and the associated uncertainty of the regional future projections  
13 obtained under the A1B scenario for the first half of the 21st century. In particular, we con-  
14 sider the regional simulation dataset from the EU-funded ENSEMBLES project, consisting  
15 of thirteen state-of-the-art RCMs run at 25km resolution over Europe.

16 While ERA40 severely underestimates both the mean NSD and its observed trend ( $-2.2$   
17 days/ decade), the corresponding RCM simulations driven by the reanalysis appropriately  
18 capture the interannual variability and trends of the observed NSD (trends ranging from  
19  $-3.4$  to  $-0.7$  days/decade,  $-2.1$  days/decade for the ensemble mean). The results driven by  
20 the GCM historical runs are quite variable, with trends ranging from  $-8.5$  to  $0.2$  days/decade  
21 ( $-1.5$  days/decade for the ensemble mean), and the greatest uncertainty by far being asso-  
22 ciated with the particular GCM used. Finally, the trends for the future 2011–2050 A1B runs  
23 are more consistent and significant, ranging in this case from  $-3.7$  to  $-0.5$  days/decade  
24 ( $-2.0$  days/decade for the ensemble mean), indicating a future significant decreasing trend.  
25 These trends are mainly determined by the increasing temperatures, as indicated by the in-  
26 terannual correlation between temperature and NSD ( $-0.63$  in the observations), which is  
27 preserved in both ERA40- and GCM-driven simulations.

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29 occurrence · snowfall trends · climate change

## 30 1 Introduction

31 The analysis of climate trends has become an important research topic during the last  
32 decades. As a result many global and regional trend studies are nowadays available, mostly  
33 for temperature and precipitation (see, e.g. Trenberth et al., 2007). However, other vari-  
34 ables of interest —such as snow— have received less attention. Snow, as a component of  
35 the cryosphere, has an important role in the water cycle and surface energy budget (Lemke  
36 et al., 2007; Vavrus, 2007), and it also strongly impacts socio-economic activities such as  
37 the tourism industry in some regions (Gonseth, 2013; Pons et al., 2012).

38 In the last years several studies have analyzed —using both observations and model  
39 simulations— the evolution of several indicators associated with snow: snow frequency,  
40 cover and extent, and length of the snow season, among others (Pons et al., 2010; Morán-  
41 Tejada et al., 2013; Piazza et al., 2014, etc.). In general, these studies agree on a shortening  
42 of the snow season (Choi et al., 2010) and a decreasing snow cover extent (Lemke et al.,  
43 2007) in the Northern Hemisphere at the end of the 20th century (see García-Ruiz et al.,  
44 2011, and references therein) which also continues in the 21st century (Räisänen, 2008;  
45 Räisänen and Eklund, 2012). Other studies have analyzed the influence of temperature and  
46 precipitation on snow cover trends; for instance, Clark et al. (1999) studied Eurasian winter  
47 snow extent and found that in regions where the mean winter temperature was well below  
48 zero, snow extent was mainly controlled by precipitation. However, in the transient regions  
49 where the mean winter temperature was relatively close to zero, the temperature control  
50 was dominant. This changing influence of temperature or temperature-precipitation in snow  
51 in different regions has important implications for the analysis of future projections, since  
52 the climate change signal for temperature is more robust than for precipitation in existing  
53 climate change projections. Therefore, snow projections in regions mainly influenced by  
54 temperature may also have a more robust climate change signal.

55 In Europe, a statistically significant decrease has been detected in the Alps since the  
56 early 80s in the mean snow depth, the duration of snow cover and the number of snow-  
57 fall days, with more pronounced trends in the medium and lower altitudes (Laternser and  
58 Schneebeli, 2003; Lemke et al., 2007). This decrease has been mainly attributed to an in-  
59 crease in mean temperature (Scherrer et al., 2004; Hantel and Hirtl-Wielke, 2007), mainly  
60 at lower elevations. A significant decreasing snow-pack trend has been also detected in the  
61 Pyrenees (López-Moreno, 2005; Morán-Tejada et al., 2013), but attributed in this case to  
62 changes in both precipitation and temperature due to the medium and high altitudes. In a  
63 recent work, Buisan et al. (2015) studied the relationship between the number of snow days  
64 in the Pyrenees and other factors such as elevation, distance to the sea and weather types,  
65 finding a decreasing trend for the period 1971-2000.

66 A number of recent applications of Regional Climate Models (RCMs) with respect to  
67 European snow cover and snowfall scenarios have also been carried out in the last years.  
68 These two variables are related since snow cover changes can partly be explained by changes  
69 in snowfall amounts (as reflected by a change in the number of snow days), in addition to  
70 changes in the melt rate of an existing snow pack. Steger et al. (2012) found that the RCMs  
71 are capable of simulating the general spatial and seasonal variability of Alpine snow cover  
72 and found a shortening of the snow cover season in the twenty first century projections,  
73 with temperature changes appearing to be the dominant factor for the pronounced decrease

74 in all analyzed snow parameters throughout the twenty first century. Using high resolution  
75 RCM output, de Vries et al. (2014) showed that mean and extreme snowfall in most parts  
76 of western and central Europe are projected to reduce strongly in the future (2071-2100)  
77 while in a study for northern Europe (Räisänen, 2015), twelve regional model simulations  
78 of twenty-first century climate suggest a decrease in the winter total snowfall in nearly all  
79 of the area.

80 The objective of the present study is to analyze the historical and future projected re-  
81 gional snowfall trends in a broad area of Northern Spain—including the Cantabrian Range,  
82 the Central System and part of the Iberian System and the Pyrenees— building on a pre-  
83 vious work by Pons et al. (2010) and focusing on annual snowfall occurrence (Number of  
84 Snowfall Days, NSD). These authors identified temperature as the main variable influenc-  
85 ing the interannual variability of NSD in their dataset of medium to low altitude stations  
86 (with an interannual correlation of  $-0.72$ ). Since the climate change signal for temperature  
87 is robust (as mentioned earlier in this introduction), this is an opportunity to explore fu-  
88 ture snowfall projections in this area. In particular, we explore the ability of an ensemble of  
89 regional climate models from the EU-funded ENSEMBLES project to properly reproduce  
90 the observed trends (both with “perfect” reanalysis boundary conditions and driven by the  
91 GCM outputs from the 20C3M historical scenario) and analyze the climate change signal  
92 produced in a future scenario (A1B) until the mid 21st century. We also analyze whether  
93 the observed relationship between temperature and NSD is preserved in the historical and  
94 future projections.

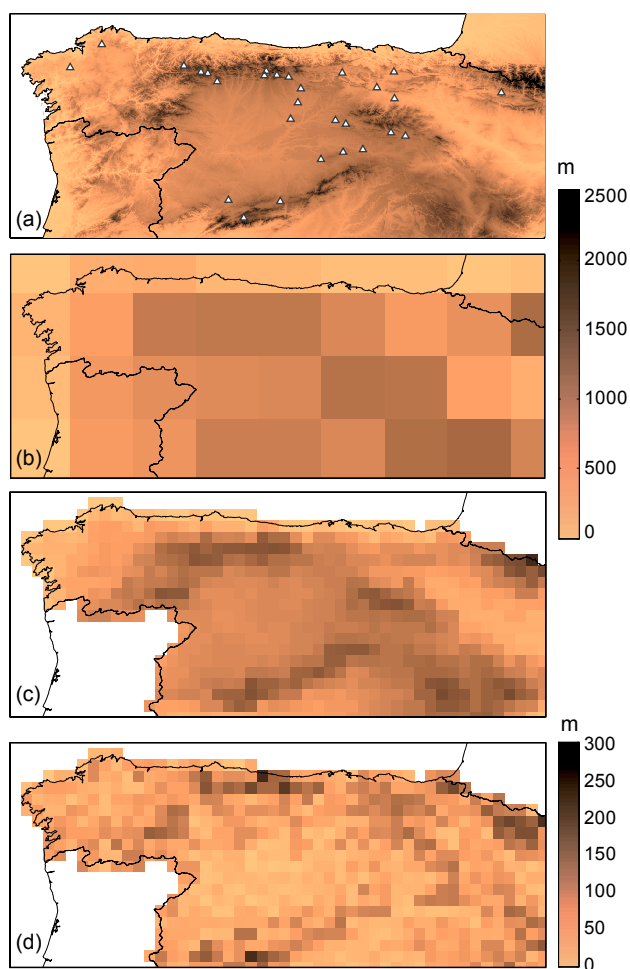
95 In the first part of the paper we present the different datasets considered in this work  
96 (Sec. 2). Secondly, we analyze the capability of the ERA40-driven RCM simulations to  
97 reproduce the climatology and trends observed for the snowfall frequency in the period  
98 1961–2000 (Sec. 3). Then, we consider the GCM-driven simulations in order to analyze the  
99 trends projected by the RCMs under the historical (20C3M) and future (A1B, for the period  
100 2011–2050) scenarios (Sec. 4). In section 5 we study the correlation with temperature and,  
101 finally, we synthesize the main results and conclusions of this work (Sec. 6).

## 102 **2 Area of Study and Available Data**

### 103 **2.1 Observations**

104 In this paper we consider 33 stations at medium to low heights (ranging from 60 to 1350 m)  
105 in Northern Iberia (see Fig. 1(a) and Table 1 for more details) which have been analyzed by  
106 Pons et al. (2010) in a previous study; the stations belong to the Spanish Meteorological State  
107 Agency (AEMET). Daily data for snowfall occurrence and mean temperature (obtained as  
108 the mean value of maximum and minimum temperatures) was available for the period 1961-  
109 2000. Snowfall occurrence is an indication of whether snowfall was reported in a 24-hour  
110 period, regardless of the amount (measurable snow on the ground is not even required to  
111 issue a report). The annual NSD inferred from this binary variable is then used throughout  
112 the study. By convention, the years considered in this paper don’t correspond to natural  
113 years: they cover the period from September to May, preventing the winters to be artificially  
114 split into two separate years (summer months June, July and August—when practically no  
115 snowfall occurs— were excluded from this study).

116 The analysis of temperature is included in this work in order to explore the correlations  
117 with snowfall occurrence in present and future climates, following the results obtained in  
118 Pons et al. (2010) in which this variable showed the highest correlation. However, in order



**Fig. 1** (a) Orography of the Northern Iberian peninsula as given by GTOPO30 and spatial distribution of the stations used in the study (see Table 1 for geographical details). (b) ERA40 orography. (c) Mean and (d) standard deviation of the orography of the RCMs over the regular 25km grid.

119 to compare the observations with the RCM data, some stations will be discarded in this study  
120 (see sec. 2.3 for more details).

121 In the previous study by Pons et al. (2010) all the analysis was focused on the period  
122 1975-2000, since the observed trend was found to be more significant for this shorter period  
123 than for the whole available period (1961-2000). In this study, however, the whole period  
124 has been considered to harmonize the length of the historical (1961-2000) and future (2011-  
125 2050) periods analysed. Moreover, the GCM-driven RCM runs have not been developed  
126 to reproduce the interannual variability observed in this period but the historical trend and,  
127 therefore, the analysis of a shorter period could lead to misleading results.

Station	Lat.	Lon.	Height	NSD	NSD <sub>r</sub>	Height <sub>μ</sub>	Height <sub>σ</sub>	Height <sub>d</sub>
GRADO #*	43.38	-6.06	60	2.1	2.0	507	114.5	447
SANTESTEBAN #*	43.13	-1.66	131	4.8	4.8	579	104.4	448
VILLACARRIEDO #*	43.23	-3.80	212	4.8	4.8	719	82.8	507
MONTAOS-ORDES	43.04	-8.42	306	1.7	1.6	266	43.3	-40
AS PONTES DE GARCIA #	43.45	-7.86	343	4.0	3.8	522	62.1	179
CENICERO INDUSTRIAL #	42.48	-2.64	430	8.7	8.3	586	86.0	156
MIRANDA DE EBRO #	42.68	-2.96	520	9.8	9.2	598	62.1	78
URRUNAGA PRESA	42.96	-2.65	540	7.5	7.1	651	76.6	111
VILLARCAYO	42.94	-3.57	595	14.1	13.4	833	61.8	238
JAVIERREGAY	42.59	-0.74	690	8.9	8.7	915	145.4	225
MONZON DE CAMPOS #	42.12	-4.49	754	7.9	7.9	782	30.0	28
OSORNO	42.41	-4.36	809	10.0	9.6	775	54.9	-34
SAN MIGUEL DE BERNUY	41.40	-3.95	839	12.9	13.1	923	50.4	84
PANTANO DE STA. TERESA #	40.67	-5.60	840	13.1	12.7	911	27.6	71
ALAR DEL REY #	42.66	-4.31	851	17.6	17.1	921	53.9	70
SAN ESTEBAN DE GORMAZ #	41.57	-3.20	860	12.7	12.6	960	18.1	100
RETUERTA	42.03	-3.51	900	20.9	19.6	962	21.6	62
LINARES DEL ARROYO #	41.53	-3.56	911	14.0	13.6	936	60.9	25
BESCOS DE GARCIPOLLERA *	42.63	-0.50	920	14.8	14.1	1367	192.8	447
TORRECILLA DEL MONTE	42.09	-3.69	949	7.9	7.9	963	20.5	14
LA MAGDALENA #	42.78	-5.80	998	17.6	16.9	1088	118.0	90
PANTANO DE CERVERA	42.87	-4.53	1000	23.7	23.3	1129	115.1	129
GARRAY	41.82	-2.45	1010	9.8	9.7	1151	40.8	141
PANTANO DE REQUEJADA #*	42.91	-4.53	1024	26.8	26.4	1409	103.0	385
BOCA DE HUERGANO	42.97	-4.93	1104	36.5	35.0	1389	79.2	285
PRIORO #	42.89	-4.96	1123	35.9	35.7	1344	111.5	221
AVILA 'OBSERVATORIO'	40.65	-4.68	1130	17.5	16.7	1158	46.1	28
EMBALSE CUERDA DEL POZO	41.88	-2.70	1150	27.4	26.9	1197	138.4	47
RABANAL DE LUNA #	42.93	-5.97	1150	36.5	36.0	1394	50.7	244
GENESTOSO	43.06	-6.39	1180	50.5	50.0	1356	161.0	176
HUERGAS DE BABIA	42.96	-6.09	1222	46.6	46.4	1408	62.0	186
PANTANO DE CAMPORREDONDO #	42.90	-4.74	1253	39.6	39.2	1409	93.1	156
ZAPARDIEL DE LA RIBERA	40.36	-5.33	1353	27.7	27.9	1255	80.2	-98
Mean Values	42.42	-4.26	823	18.0	17.6	981	77.8	158

**Table 1** Name, location (latitude and longitude, in degrees), height (m) and mean annual number of snow days (NSD) of all stations for the period 1961–2000. The last four columns correspond to the closest RCM grid points to each station for the nine RCMs and indicate the multi-RCM mean annual number of snow days (NSD<sub>r</sub>) for the same period, the mean (Height<sub>μ</sub>) and the standard deviation (Height<sub>σ</sub>) of the elevation, and its difference with the actual height of the station (Height<sub>d</sub>). The stations in which this height difference was greater than 300 m are highlighted with an asterisk (\*). Stations with temperature records are indicated with #.

## 128 2.2 Model simulations

129 The EU-funded project ENSEMBLES (<http://www.ensembles-eu.org>) was a collaborative  
130 effort of different European meteorological institutions focused on the generation of climate  
131 change scenarios over Europe, including a large variety of communities and state-of-the-art  
132 methodologies and techniques. In particular, dynamical downscaling was performed using  
133 different regional climate models (RCMs) run by different institutions (see the list in Table  
134 2) over a common area covering the entire continental European region and with a common  
135 resolution of approx. 25 km, although with different native rotated grids for each model (the  
136 ICTP model is not considered in this study since it doesn't include the variable snow flux).

137 The RCMs were driven both by the ERA40–reanalysis of the European Centre for  
138 Medium Range Weather Forecasts (ECMWF, Uppala et al., 2005), for a common period

**Table 2** Summary of the twelve RCMs from the ENSEMBLES project with snow data. The columns are the acronym used in the paper, the institution running the simulation, the model used and their corresponding references. The RCMs marked with an asterisk (\*) were discarded in this study to avoid model redundancy (HRQ3 and HRQ16) or due to problems with the dataset (SMHI).

Acronym	Institution	Model	Reference
C4I	Comunity Climate Change Consortium for Ireland	RCA3	Samuelsson et al. (2011)
CNRM	Centre National de Recherches Meteorologiques	ALADIN-Climat	Radu et al. (2008)
DMI	Danish Meteorological Institute	HIRHAM	Christensen et al. (2006)
ETHZ	Swiss Federal Institute of Technology	CLM	Jaeger et al. (2008)
HRQ0	Hadley Center/UK MetOffice	HadRM3 Q0	Collins et al. (2006)
HRQ3(*)	Hadley Center/UK MetOffice	HadRM3 Q3	Collins et al. (2006)
HRQ16(*)	Hadley Center/UK MetOffice	HadRM3 Q16	Collins et al. (2006)
KNMI	Koninklijk Nederlands Meteorologisch Instituut	RACMO	van Meijgaard et al. (2008)
METNO	The Norwegian Meteorological Institute	HIRHAM	Haugen and Haakensatd (2005)
MPI	Max Planck Institute for Meteorology	M-REMO	Jacob et al. (2001)
SMHI(*)	Swedish Meteorological and Hydrological Institute	RCA	Kjellström et al. (2005)
UCLM	Universidad de Castilla la Mancha	PROMES	Sanchez et al. (2004)

**Table 3** Matrix of the GCM–RCM coupling experiments from the ENSEMBLES project (van der Linden and Mitchell, 2009) used in this study. GCMs and RCMs are shown in columns and rows, respectively. G1: ARPEGE, G2: BCM, G3: ECHAM5-r3, G4: HadCM3-Q0, G5: HadCM3-Q16.

RCM\GCM	ERA40	G1	G2	G3	G4	G5
C4I	x					x
CNRM	x	x				
DMI	x	x	x	x		
ETHZ	x				x	
HRQ0	x				x	
KNMI	x			x		
METNO	x		x		x	
MPI	x			x		
UCLM	x				x	

139 of 40 years (1961–2000), and by different Global Circulation Models (GCMs) based on the  
 140 20C3M (1961–2000) and A1B (2001–2050) scenarios (Nakićenović, 2000; Nakićenović  
 141 and Swart, 2000); in all cases, daily records of snow flux and temperature were downloaded  
 142 from the DMI ENSEMBLES server (<http://ensemblesrt3.dmi.dk/data>; the data used corre-  
 143 spond to the latest version available up to February 2015). The RCM simulations under both  
 144 the 20C3M (historical) and A1B (future) scenarios were driven by one or several GCMs, as  
 145 shown in Table 3.

146 A basic quality control of the RCM data revealed some problems in the SMHI dataset,  
 147 exhibiting very small NSD values. Therefore, the SMHI model was not considered in this  
 148 paper. Moreover, in order to avoid model duplicity, only the version with ‘normal’ climate  
 149 sensitivity of the Hadley models (HRQ0) was included in the ensemble, discarding the ver-  
 150 sion with ‘low’ (HRQ3) and ‘high’ (HRQ16) climate sensitivities (Collins et al., 2010).

151 Besides the RCM outputs we also analyze the global ERA40 reanalysis (Uppala et al.,  
 152 2005), produced by the European Centre for Medium Range Weather Forecasts (ECMWF)  
 153 in collaboration with many institutions. This reanalysis was obtained from the ECMWF’s  
 154 MARS server for the period September 1961 to August 2000 on its native resolution of  
 155 1.125° x 1.125°. An analysis of the GCM output itself was not possible as neither the  
 156 CERA–database of the World Data Center for Climate (<http://cera-www.dkrz.de/CERA/>)

157 nor the DMI ENSEMBLES server (for the HadCM3-Q0 and HadCM3-Q16 models) pro-  
158 vides snowfall data for these models.

### 159 2.3 Data Harmonization

160 In order to avoid the known drizzle effect of the climate models (Hay and Clark, 2003;  
161 Piani et al., 2010) which leads to an overestimation of the probability of rain and snowfall  
162 occurrence, snowfall frequency (NSD) was obtained from snow flux ( $\text{kg m}^{-2} \text{s}^{-1}$ ) using a  
163 threshold of 1 mm/day ( $1/86400 \text{ kg m}^{-2} \text{s}^{-1}$ ). Moreover, for consistency with observations,  
164 mean temperature was obtained as the mean value of the maximum and minimum daily  
165 temperatures provided by the models.

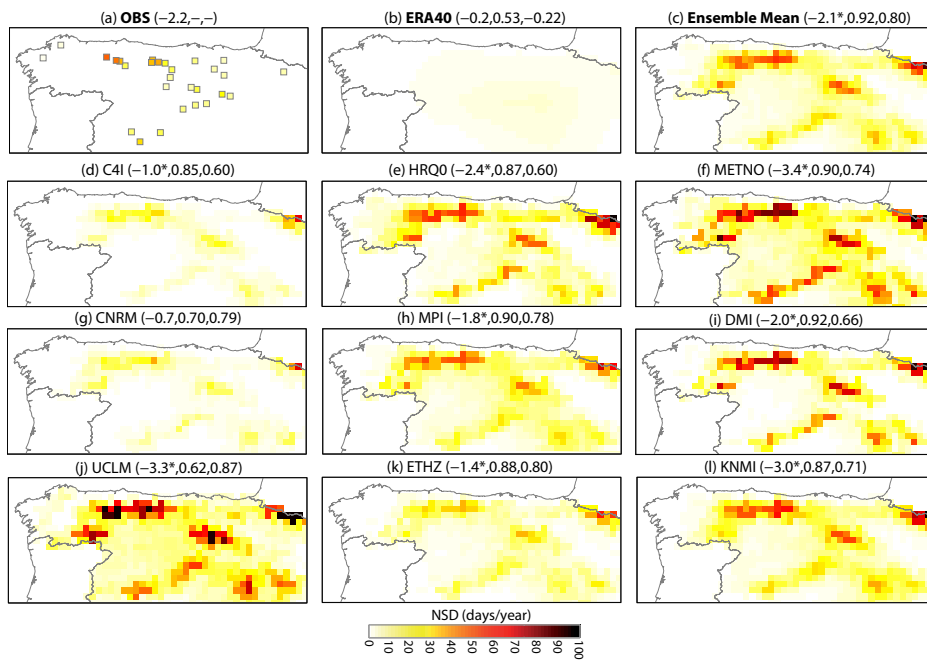
166 Since each RCM has a different rotated grid, all of them were interpolated by nearest  
167 neighbours to a common  $0.2^\circ$  (approx. 20km) regular grid shown in Fig. 1. Fig. 1c-d shows  
168 the mean and standard deviation of the RCM elevations interpolated to this common grid.  
169 Note that the highest variability is obtained in regions with complex orography. In order to  
170 properly compare the stations and the RCM results, the height of each of the 33 stations was  
171 compared to the ensemble mean height of the closest RCM grid point (Column 7 in Table  
172 1), discarding those stations differing by more than 300 m (highlighted with an asterisk in  
173 Table 1). This criterion was chosen since the maximum inter-model standard deviation of  
174 the orography in the study region is around 300 m and therefore the station elevation will be  
175 close to the grid cell orography of most RCMs. Hereinafter we will consider the resulting  
176 28 stations. This implies that only 12 of the initial 16 stations with temperature records will  
177 be considered when analyzing the correlation between NSD and temperature.

### 178 3 ERA40-driven Simulations

179 In this part of the study we use the ERA40-driven RCM simulations in order to analyze the  
180 capability of the models to reproduce the NSD climatology, trend and interannual variability  
181 observed at the 28 stations (see Table 1 and Sec. 2.1 for more details).

182 Figure 2 shows the annual NSD climatologies for the period 1961–2000 given by the  
183 observations, ERA40 and the RCMs driven by ERA40. In general terms, all the RCM simu-  
184 lations exhibit a similar spatial pattern, with spatial correlations with observations ranging  
185 between 0.58 and 0.87 (see the last numbers in the titles of Fig. 2). The most noticeable  
186 difference is that simulations for C4I, CNRM and ETHZ (panels d, g, and k) underestimate  
187 snowfall. In order to explore this difference, a further analysis of all the RCMs orography  
188 and mean temperature fields was performed (not shown in this paper). The surface orog-  
189 raphy is realistically represented in all cases and these three models don't exhibit higher  
190 mean temperature fields than the rest; hence, snowfall underestimation is probably due to  
191 deficiencies in the parameterization of precipitation microphysics in these models.

192 In order to validate the performance of the RCMs we compare the observed and simu-  
193 lated trends and the interannual variability of the corresponding spatially averaged annual  
194 series. To this aim we consider the mean annual NSD value over the 28 stations (for the  
195 observations) and over the closest model gridboxes to the 28 stations (for the simulations).  
196 The first number in the title of each panel in Fig. 2 shows the trends of the corresponding  
197 series —significant trends at a 95% level are marked with an asterisk,— whereas the second  
198 number indicates the (inter-annual) correlation for the period 1961–2000.



**Fig. 2** Climatologies of NSD in the period 1961–2000 given by (a) the observations in the 28 stations (b) ERA40 and (d)–(l) the ERA40-driven simulations of the eleven RCMs used in this study (see Table 2)—the RCM ensemble mean results are shown in panel (c).— The first number in the title of each panel shows the spatially averaged NSD trend in days/decade; trends significant at the 95% level are highlighted with an asterisk. The second number gives the temporal (interannual) correlation between the simulated and observed NSD time series, and the third number the corresponding spatial correlation. In all cases, only the 28 RCM gridboxes closest to the stations were considered in the analysis.

199 All the RCMs present negative trends —significant except the CNRM model,— ranging  
 200 from  $-3.4$  days/decade to  $-0.7$  days/decade, with similar slopes than the observed ones,  
 201 with the exception of the models which underestimate snowfall (panels d, g and k). Note  
 202 that higher trends would be obtained for these models if they were bias-corrected (rescaled)  
 203 to avoid underestimation; however we keep the original raw RCM values to assess to per-  
 204 formance of the original ensemble, which will be subsequently used later in the paper to  
 205 infer future trend projections driven by different GCMs. Moreover, all models exhibit high  
 206 interannual correlation coefficients (over 0.85 with the exception of CNRM and UCLM),  
 207 thus indicating a good performance in reproducing the temporal evolution of the NSD.

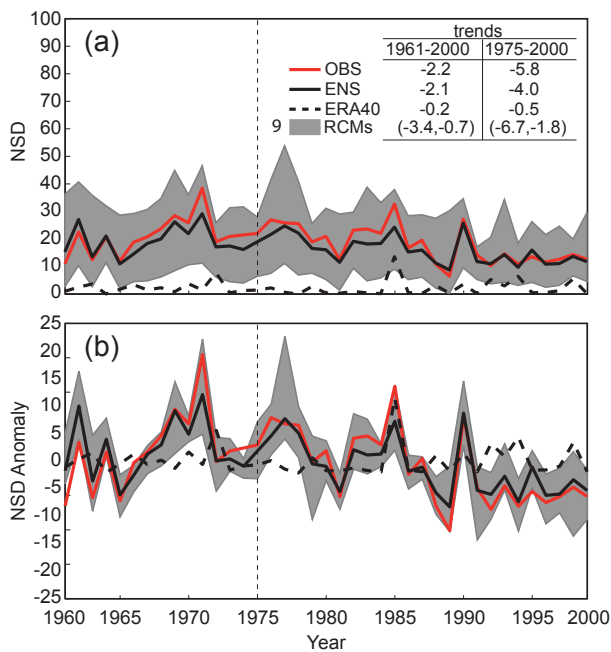
208 In order to appreciate more clearly its temporal evolution, Fig. 3 shows the interannual  
 209 variability of the NSD averaged over the 28 stations/gridboxes in the period 1961–2000 for  
 210 the ensemble of nine RCMs (indicated by the grey shadow, spanning from the minimum to  
 211 the maximum value), together with the observations (red line), the ERA40 direct outputs  
 212 (dashed black line), and the ensemble mean (black line). Fig. 3b shows the correspond-  
 213 ing anomaly series, obtained after removing the mean of each of the models. Firstly, note  
 214 that the observed NSD values are contained within the ensemble of RCMs. Secondly, note  
 215 that the ensemble mean adequately reproduces the observed interannual variability —with  
 216 a correlation of 0.92 in the period 1961–2000, as shown in Fig. 2c— and exhibits a very  
 217 similar trend to the observations. Finally, ERA40 clearly underestimates the observed NSD



218 (Fig. 2b and Fig. 3) and is not able to reproduce the observed interannual variability (with  
 219 a correlation coefficient of 0.53) nor the trend. The lower resolution of ERA40 and hence  
 220 its lower orography (see Fig. 1b) is probably the main reason for its poor performance in  
 221 representing the observed NSD values. This clearly shows the added value of the RCMs in  
 222 this study, since they allow to properly reproduce the observed NSD climatology and trend  
 223 when downscaling a reanalysis which simulates inadequately this variable.

224 Fig. 3 also displays the trend values for the period 1975-2000, clearly showing larger  
 225 trends for the shorter period due to a small increase in the observed NSD between 1960  
 226 and 1970, which is reproduced by the ERA40-driven RCM simulations. However, all the  
 227 analysis in this paper was performed using the 1961-2000 period for the reasons explained  
 228 at the end of section 2.1.

229 A similar trend analysis was also performed for mean temperature obtaining a larger  
 230 agreement among all RCMs (ranging from 0.1 to 0.2 °C/decade) and the observations (0.2  
 231 °C/decade), as shown in the first column of Table 4. In this case the temperature trend  
 232 obtained directly from the ERA40 reanalysis series (0.4 °C/decade) was closer to the obser-  
 233 vations than the NSD trend.



**Fig. 3** (a) Annual NSD observations (red line) and RCM outputs from ERA40-driven simulations (grey shadow), averaged over the 28 stations/gridboxes. (b) Annual NSD anomalies obtained after removing the models' means. The solid and dashed black lines show the ensemble mean (ENS) and the direct ERA40 output, respectively. The number in the left of the RCM legend indicates the number of members forming the ensemble. The inset shows the trends (NSD/decade) over the 1961-2000 and 1975-2000 periods for the different models (the minimum and maximum values are shown for the RCM ensemble).

**Table 4** Trends of NSD (days/decade) and temperature ( $^{\circ}\text{C}/\text{decade}$ ) during the period 1961–2000 for the RCMs nested to ERA40 and to the different GCMs in the 20C3M scenario—the last column shows the results for the multi-GCM ensemble.— The last row shows the multi-RCM ensemble mean (ENS) corresponding to each of the driving GCMs. Only the trends highlighted with an asterisk (\*) are significant at a 95% level. Note that for the observations (ERA40 reanalysis) series, there is a trend of  $-2.2$  ( $-0.2$ ) days/decade for the NSD and  $0.2^*$  ( $0.4^*$ )  $^{\circ}\text{C}/\text{decade}$  for the temperature (not shown in the table).

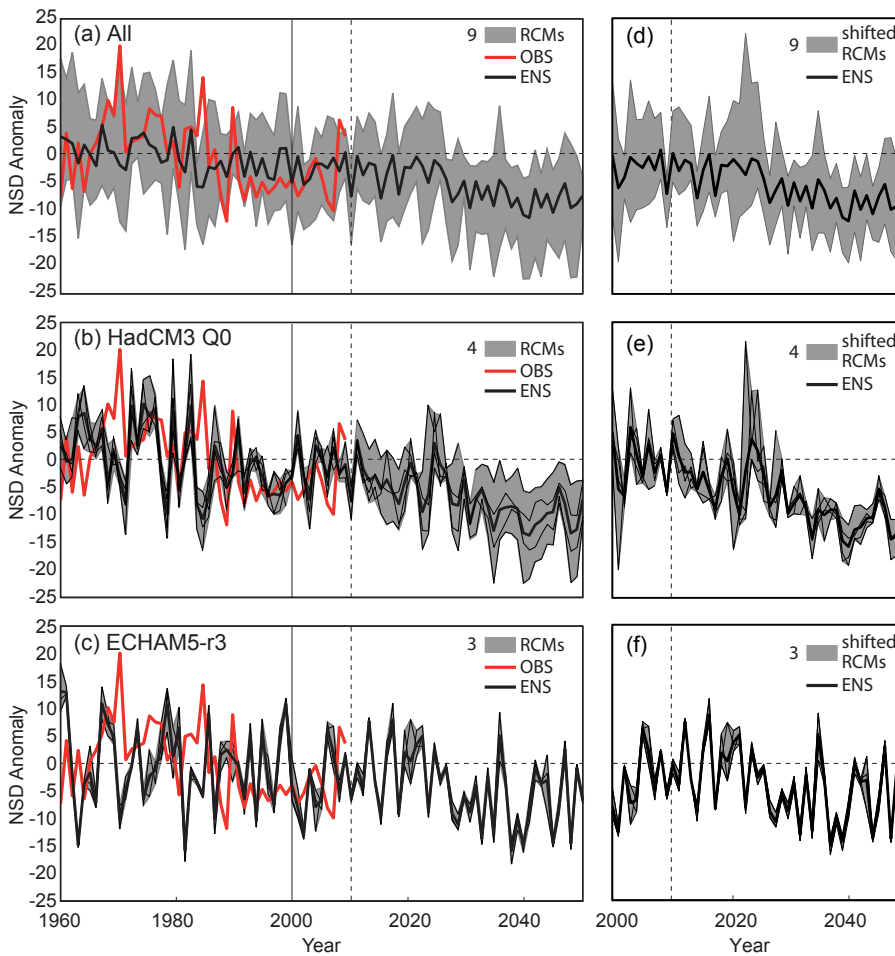
RCM\GCM	ERA40	G1	G2	G3	G4	G5	Multi-GCM
C4I	(-1.0*, 0.2)					(-0.2, 0.1)	
CNRM	(-0.7, 0.1)	(-0.6, 0.2*)					
DMI	(-2.0*, 0.2*)	(-0.4, 0.2*)	(-0.6, 0.0)	(-0.6, 0.1)			(-0.5, 0.1*)
ETHZ	(-1.4*, 0.1)				(-1.3, 0.3*)		
HRQ0	(-2.4*, 0.2*)				(-2.4*, 0.4*)		
KNMI	(-3.0*, 0.1)			(-0.4, 0.1)			
METNO	(-3.4*, 0.1)		(-1.2, 0.0)		(-2.4, 0.2*)		(-1.8, 0.1)
MPI	(-1.8*, 0.2)			(0.2, 0.1)			
UCLM	(-3.3*, 0.2*)				(-8.5*, 1.0*)		
ENS	(-2.1*, 0.2)	(-0.5, 0.2*)	(-0.9, 0.0)	(-0.3, 0.1)	(-3.6*, 0.5*)	(-0.2, 0.1)	(-1.5*, 0.2*)

#### 234 4 GCM-driven Projections

235 Table 4 shows the trends corresponding to the ensemble of RCM–GCM couplings for the  
 236 same period as in the previous section (1961–2000), considering the historical 20C3M runs.  
 237 In some cases these trends are comparable to those obtained for the ERA40–driven simula-  
 238 tions (the trends for the ERA40–driven simulations are also included in the table to facilitate  
 239 the comparison) but the variability of the results is largely conditioned by the particular driv-  
 240 ing GCM, both for snowfall and temperature. The multi-model GCM–RCMs ensemble mean  
 241 shows a good performance, with significant trends of  $-1.5$  days/decade and  $0.2$   $^{\circ}\text{C}/\text{decade}$ ,  
 242 similar to the observed ones ( $-2.2$  days/decade and  $0.2$   $^{\circ}\text{C}/\text{decade}$ ).

243 Table 5 shows the corresponding trends for the future (2011–2050) projections corre-  
 244 sponding to the A1B scenario runs. Note that most of the trends are significant in this pe-  
 245 riod, ranging from  $-3.7$  to  $-0.5$  days/decade, indicating a significant decreasing trend for  
 246 the NSD of  $-2.0$  days/decade, according to the multimodel ensemble mean.

247 In order to graphically illustrate the influence of the driving GCM on the variability of  
 248 the ensemble, Fig. 4a–c shows the composite series of the historical (20C3M) and future  
 249 (A1B) anomalies (w.r.t. the 1961–2000 period) for the ensemble of all RCM–GCM simu-  
 250 lations and those RCMs coupled to the HadCM3–Q0 global model and the ECHAM5–r3  
 251 global model separately (the two GCMs with the largest number of RCMs coupled to them,  
 252 four and three, respectively). The models coupled to ECHAM5–r3 (panel c) show very lit-  
 253 tle spread while those coupled to HadCM3–Q0 show a considerably greater spread in the  
 254 A1B period (2001–2050). This change is due to a discontinuity caused by the changing sce-  
 255 nario of the corresponding GCMs in year 2000 (from 20C3M to A1B), as shown in Figures  
 256 Fig. 4d–f, where the corresponding anomaly series for the 2001–2050 have been re-centered  
 257 (shifted to the ensemble mean). The resulting series show a similar interannual variability  
 258 clearly illustrating that the greatest uncertainty by far is associated with the particular GCM  
 259 used.



**Fig. 4** Observations and historical (20C3M, 1961-2000) and future (A1B, 2001-2050) anomalies (w.r.t. the mean of the period 1961-2000) for the ensemble of all RCMs (a,d) and for the sub-ensembles driven by the HadCM3 Q0 (b,e) and ECHAM5-r3 (c,f). The mean of the anomalies of each of the RCMs in the period 2001-2050 has been shifted to the ensemble mean in panels (d-f) to avoid the shifts in the RCM simulations between the 20C3M and A1B periods. In all cases the red line represents the observations (OBS) and the black bold line represents the mean of the ensembles (ENS). In panels b-c and e-f the black thin lines represent each RCM-GCM simulation. The numbers in the legends indicate the number of members forming each ensemble.

## 260 5 Correlation with temperature

261 The relationship of NSD with annual rain frequency and mean temperature was analyzed  
 262 by Pons et al. (2010), reporting correlation coefficients of 0.27 and  $-0.72$ , respectively,  
 263 for the period 1957–2002. Taking into account this result, in the present paper we analyze  
 264 only the correlation with mean temperature synthesizing the results in Table 6 (note that  
 265 these results are based on only 12 stations with temperature records; see Table 1). This table  
 266 shows the correlations considering the outputs of the RCMs nested with ERA40 and with

**Table 5** Trends of NSD (days/decade) and temperature ( $^{\circ}\text{C}/\text{decade}$ ) during the period 2011–2050 for the RCMs nested to the different GCMs in the A1B scenario runs. Only the trends highlighted with an asterisk (\*) are significant at a 95% level.

RCM\GCM	G1	G2	G3	G4	G5	Multi-GCM
C4I					(-0.5*, 0.4*)	
CNRM	(-1.2*, 0.4*)					
DMI	(-1.1*, 0.4*)	(-1.5, 0.2*)	(-2.6*, 0.3*)			(-1.9*, 0.3*)
ETHZ				(-1.5*, 0.6*)		
HRQ0				(-3.0*, 0.6*)		
KNMI			(-1.9, 0.3*)			
METNO		(-3.2*, 0.2*)		(-3.7*, 0.5*)		(-3.6*, 0.4*)
MPI			(-2.1, 0.3*)			
UCLM				(-2.3*, 0.4*)		
ENS	(-1.2*, 0.4*)	(-2.3*, 0.2*)	(-2.2*, 0.3*)	(-2.6*, 0.5*)	(-0.5*, 0.4*)	(-2.0*, 0.4*)

**Table 6** Correlations between the NSD and temperature simulated for the RCMs nested with ERA40 (second column) and with the different GCMs considering both the 20C3M (first number in the parenthesis) and A1B (second number) scenarios for the periods 1961–2000 and 2011–2050, respectively. Note that the correlation in the first period between the observed (reanalysis) series was  $-0.63$  ( $-0.32$ ), not shown in the table.

RCM\GCM	ERA40	G1	G2	G3	G4	G5	Multi-GCM
C4I	-0.61					(-0.24, -0.42)	
CNRM	-0.40	(-0.29, -0.69)					
DMI	-0.70	(-0.67, -0.75)	(-0.68, -0.78)	(-0.66, -0.77)			(-0.59, -0.81)
ETHZ	-0.56				(-0.76, -0.67)		
HRQ0	-0.73				(-0.80, -0.82)		
KNMI	-0.62			(-0.34, -0.65)			
METNO	-0.60		(-0.61, -0.79)		(-0.85, -0.80)		(-0.81, -0.88)
MPI	-0.65			(-0.46, -0.67)			
UCLM	-0.20				(-0.92, -0.76)		
ENS	-0.61	(-0.51, -0.76)	(-0.66, -0.80)	(-0.50, -0.71)	(-0.90, -0.84)	(-0.24, -0.42)	(-0.76, -0.89)

267 the different GCMs under both the 20C3M and A1B scenarios, for the periods 1961–2000  
268 and 2011–2050, respectively.

269 Excluding CNRM and UCLM, all the RCMs forced with reanalysis data are able to  
270 reproduce reasonably well the observed dependence between the NSD and temperature in  
271 the period 1961–2000, with correlation values ranging from  $-0.73$  to  $-0.56$ . Moreover,  
272 when comparing the results corresponding to the historical runs (20C3M) and the future  
273 scenarios (A1B) we found that the correlation is larger for the latter in most of the cases  
274 which may be related to the higher trends simulated by the regional models under the A1B  
275 scenario.

## 276 6 Conclusions

277 In this paper we have analyzed the performance of the ERA40– and GCM–driven RCM  
278 simulations to reproduce the spatial pattern and the interannual variability of the number of  
279 snowfall days in 28 stations of northern Spain, following the study by Pons et al. (2010).

280 One of the most clear conclusions of this work is that ERA40 cannot be used on its  
281 own in NSD trend assessment studies, although it properly reproduces the trend of temper-

282 ature (the most important variable influencing snowfall in this region). Its low resolution is  
283 the most likely reason for not being able to represent either the interannual variability or  
284 the observed trend. However, practically all the RCM ERA40-driven simulations analyzed  
285 in this study capture properly the NSD spatial pattern (correlations ranging between 0.58  
286 and 0.87), the interannual variability (correlations between 0.62 and 0.92), as well as the  
287 observed trends of the last quarter of the 20th century (trends ranging from  $-3.4$  to  $-0.7$   
288 days/decade). Some of the models (C4I, CNRM and ETHZ) exhibited an underestimation  
289 of the climatological NSD yielding smaller trend values.

290 In the case of the GCM-driven simulations in the historical period (20C3M) the RCM  
291 results are quite variable with trends ranging from  $-8.5$  to  $0.2$  days/decade although they  
292 practically all capture the sign and, mainly in the case of the HadCM3-Q0, the inten-  
293 sity of the NSD trends of the corresponding ERA40-driven simulation. Furthermore, the  
294 multi-model ensemble mean shows a good performance, with significant trends of  $-1.5$   
295 days/decade and  $0.2$  °C/decade, similar to the observed ones ( $-2.2$  days/decade and  $0.2$   
296 °C/decade). The trends for the future GCM-driven projections (A1B scenario, 2011–2050)  
297 are more consistent and significant than the historical ones, ranging in this case from  $-3.7$   
298 to  $-0.5$  days/decade; the multi-model ensemble mean indicates future significant trends of  
299  $-2.0$  days/decade and  $0.38$  °C/decade, (33% and almost 50% higher than the ones simulated  
300 for the 1961–2000 period, respectively).

301 The correlation between the observed NSD and the temperature in the period 1961-  
302 2000 ( $-0.63$ ) is preserved by both ERA40- and 20C3M scenario GCM-driven simulations  
303 ( $-0.61$ ,  $-0.76$ , respectively). This relation between both variables is stronger in the future  
304 A1B projections ( $-0.89$ ), leading to opposite significant trends for both variables in the  
305 future.

306 Finally, another interesting result from this study is the fact that the greatest uncertainty  
307 by far in the GCM-RCM simulations is due to the particular GCM used. This is in agreement  
308 with previous results found by Déqué et al. (2012), who found that the largest source of  
309 uncertainty for temperature and precipitation in the ENSEMBLES dataset came from the  
310 GCM (with the exception of Summer for precipitation). Although no proper separation of  
311 variance analysis has been performed in this paper, the results shown in Tables 4 and 5 and  
312 Fig. 4 clearly indicate that the fraction of variance explained by the GCM is very large in  
313 this case. Therefore, special care should be taken when constructing the multi GCM-RCM  
314 matrices in ensemble experiments for regional climate change in order to properly balance  
315 the contribution of each of the GCMs.

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## 324 **7 Compliance with Ethical Standards**

325 To ensure objectivity and transparency in research and to ensure that accepted principles  
326 of ethical and professional conduct have been followed, authors should include information  
327 regarding sources of funding, potential conflicts of interest (financial or non-financial), in-  
328 formed consent if the research involved human participants, and a statement on welfare of  
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335 and in the interpretation of the scientific results.
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338 prepared to collect documentation of compliance with ethical standards and send if it is  
339 requested during peer review or after publication.

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