Applied Geography 79 (2017) 127–142

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Assessment of ski condition reliability in the Spanish and Andorran Pyrenees for the second half of the 20th century

M. Gilaberte-Búrdalo [a, b, *], J.I. López-Moreno [b], E. Morán-Tejeda [b], S. Jerez [d], E. Alonso-González [b], F. López-Martín [c], M.R. Pino-Otín [a]

[a] Universidad San Jorge, Autovía A-23 Zaragoza-Huesca km 299, Zaragoza, Spain
[b] Instituto Pirenaico de Ecología, CSIC, Zaragoza, Avenida de Montañana, 1005, 50059, Zaragoza, Spain
[c] Instituto Geográfico de Aragón, Gobierno de Aragón, Paseo María Agustín, 36, Edificio Pignatelli, 3a planta, puerta 14, 50071, Zaragoza, Spain
[d] Department of Physics, Campus de Espinardo, University of Murcia, 30100, Murcia, Spain

ARTICLE INFO

Article history:
Received 25 February 2016
Received in revised form
22 December 2016
Accepted 24 December 2016
Available online 9 January 2017

Keywords:
Climate and snow trends
Ski reliability
MM5 data
Pyrenees
Ski tourism
Temporal concurrence

ABSTRACT

In this study temporal trends of 14 climate and snow parameters related to ski conditions were analyzed for 11 ski stations located in the central Pyrenees (Spain and Andorra). We also investigated whether there was a temporal association for the analyzed parameters, such that the occurrence in a particular year of good (or bad) climate or snow conditions as represented by one parameter was similarly reflected by the other parameters. The lack of reliable climate and snow measurements was overcome by the use of simulated climate data retrieved from a high resolution hindcast simulation available for the period 1960–2006. These data were also used as inputs for an energy and mass snow energy model to obtain snow series. The results showed trends in ski reliability parameters for the 1960–2006 period. The number of days having a snowpack deeper than 30 cm and 100 cm showed declines at low and mid altitudes. The start of the ski season appears progressively delayed for all stations, and the ski season shortened. The frequency of rainy days increased at 3 stations and decreased at 8, while the frequency of days having heavy snowfall increased at 8 stations and declined at 3. Days having potential for snow-making declined at all stations. The number of days having a wind-chill < −20 °C also decreased markedly, as overall did the number of days having a wind speed greater than 80th percentile. The main findings from the assessment of temporal associations between climate and snow parameters were positive correlations between snow depth and windy conditions. Seasons having a higher frequency of very cold days had a lower frequency of heavy snowfall and rainy days. Thus, the adverse effects on the ski industry of lesser snow availability may have been partially negated by the occurrence of fewer days of closure because of high winds, or other adverse meteorological factors.

1. Introduction

Tourism has emerged as one of the largest and fastest growing industries in the global economy (Eadington & Redman, 1991). For many countries, tourism has become an important source of business activity, income, employment, and demographic recovery in mountain areas (Lasanta, Laguna, & Vicente-Serrano, 2007). For this reason, tourism is receiving increasing attention from regional politicians and land managers, and in some cases this has resulted in substantial subsidies for publicity and improvements to winter sport-related infrastructure (Gilaberte, López-Martín, Pino-Otín, & López-Moreno, 2014).

Among tourist activities, in recent decades skiing and other winter sports have become essential to the economy of mountain areas (Elsasser & Bürki, 2002). However, these activities are highly dependent on climate and weather conditions, which can be limiting factors for ski tourism. The economic viability of this activity is highly dependent of the interannual variability of the snow, which is a crucial prerequisite for the skiing industry (Elsasser & Messerli, 2001; Pons, Johnson, Rosas-Casals, Sureda, & Jover, 2012; Scott, McBoyle, & Mills, 2003; Steiger & Mayer, 2008). A lack of snow because of low precipitation or high temperatures is an immense challenge for winter sport destinations (Rixen et al., 2011), especially in the context of global warming, which is

* Corresponding author. Universidad San Jorge, Autovía A-23 Zaragoza-Huesca km 299, Zaragoza, Spain.
E-mail address: magilaberte@hotmail.com (M. Gilaberte-Búrdalo).

http://dx.doi.org/10.1016/j.apgeog.2016.12.013
0143-6228/

having major effects on many mountain areas worldwide. A reduction of the snowpack has been detected in recent decades across large parts of North America (Harpold et al., 2012), the Himalayas (Dar, Rashid, Romshoo, & Marazi, 2014), the Mediterranean mountains (López-Moreno, Goyette, Vicente-Serrano, & Beniston, 2011a), the Italian and Swiss alps (Marty, 2008; Valt, Cagnati, Crepaz, & Marigo, 2005), the Pyrenees (López-Martín, Cabrera-Mollet, & Cuadrat-Prats, 2007; López-Moreno, 2005), northern Greece (Baltas, 2007), low elevation areas in Slovakia (Vojtek, Faško, & Šťastný, 2003), and the Bulgarian mountains (Brown & Petkova, 2007). Witmer (1986) proposed the "100 day rule" to link skiing potential to snow availability, and this rule has frequently been applied in subsequent studies (Abegg, 1996; Abegg, Agrawala, Crick, & de Montfalcon, 2007; Dawson & Scott, 2010; Elsasser & Bürki, 2002; Koenig & Abegg, 1997; Moen & Fredman, 2007; Pons et al., 2012; Scott et al., 2003, 2007; Steiger, 2010). This rule postulates that a ski resort has natural ski reliability if there is sufficient snow cover (at least 30 cm) for 100 days annually between December and April in 7 of every 10 years. More recently, this indicator has been questioned because the 30-cm threshold is not equally applicable to all ski resorts given their different characteristics (Pons, López-Moreno, Rosas-Casals, & Jover, 2015), and because the thickness and longevity of snow cover is normally estimated for natural snow, with no account taken of the production of artificial snow. The possibility of artificial snowmaking and manipulation of the snow on ski slopes (including grooming and alteration of the surface roughness) have been incorporated into recent vulnerability assessments (François, Morin, Lafaysee, & George-Marcelpoil, 2014; Pons et al., 2015; Steiger, 2010).

Compared with the number of studies that relate snow abundance and snowpack duration with skiability, almost no studies have considered the impacts of other climate variables that may be contributing to skiability at ski resorts. These variables, which may also influence the number of skiers, include the frequency of high winds and heavy snowfall days (probably the main cause of ski station closure), and rainy or extremely cold days. An interesting aspect of these issues is that for some specific ski locations the relationship of skiability to snow or climate parameters can be counterintuitive; for example, a snow-rich year may be associated with adverse weather conditions, or snow-poor years might be associated with anticyclonic or temperature conditions that permit the production of artificial snow during the night. Various instances of this have occurred recently in the Spanish Pyrenees. During the Christmas period in 2014, sunny weather conditions attracted a large number of skiers despite the very poor snow conditions, which caused the closure of many of ski slopes. The opposite occurred during winter 2012–2013, when the snow depths reached record levels but skiing was problematic because of blocked roads, the occurrence of many rainy days, and the very high risk of avalanche. The relative absence of studies on this aspect of skiability has probably been exacerbated by the lack of reliable climatic or meteorological data available to perform sound analyses. Data scarcity is a significant problem with respect to the Pyrenees, and for this reason we used the outputs of a mesoscale model run at high resolution over the study area driven by reanalysis data to retrieve climate parameters related to skiability and develop a snow energy balance model ("Snobal"; Marks, Domingo, Susong, Link, & Garen, 1999) that permitted us to simulate snow evolution at the studied ski stations.

The aims of the present study were: i) to assess the temporal evolution of climate and snow conditions related to ski tourism during the period 1960–2006 at 11 ski stations of the central Pyrenees; and ii) to analyze correlations between snow and climate variables over this period to enable assessment of whether there was a temporal correlation.

2. Study area

2.1. Geographic and climate characteristics

The Pyrenees is a mountain range located in the northeast of the Iberian Peninsula, bounded by the Mediterranean Sea to the east and the Atlantic Ocean to the west. The Pyrenees extends over 425 km from west to east, and constitutes a natural border between Spain and France. The width (north–south) in the central part of the range is 150 km, and declines towards the west and east. Elevations (m a.s.l.) vary from 500 m in some valley bottoms to 3404 m at the summit of Aneto Peak, with much of the area located above 1500 m (López-Moreno & García-Ruiz, 2004).

The climate is characterized by a progressive transition from Atlantic Ocean conditions in the west to Mediterranean conditions in the east. Thus, the central Pyrenees has a mix of both characteristics, with strong continental features. The maximum precipitation occurs during winter in the western part, and during spring and autumn in the east (García-Ruiz, Berguería, López-Moreno, Lorente, & Seeger, 2001). Much of the winter precipitation falls as snow from November to April, resulting in the development of a generally continuous snowpack above 1600–1700 m a.s.l. (López-Moreno & Nogués-Bravo, 2006).

The temperature is strongly influenced by topographic factors that result in an average rate of decline of 0.65 °C per 100 m increase in elevation (Del Barrio, Creus, & Puigdefábregas, 1990). From December to April the 0 °C isotherm is at approximately 1700 m a.s.l., above which the accumulated snow remains for long periods. Wind is an important climatic element in the Pyrenees that usually blows from the northwest; to a lesser extent from the north, west, and east (López-Moreno & Vicente-Serrano, 2006). When fronts arrive from the north and northwest, the moisture mostly discharges to the north and near the main divide of the Pyrenees (normally following the French–Spanish border), and as a consequence of the Foehn effect, dry and warm air masses arrive on the southern slopes of the Spanish Pyrenees. These results in there being marked differences between the Spanish and French mountain ranges in terms of snow accumulation, and this has direct effects on ski stations.

2.2. Ski stations characteristics

The 11 ski stations selected for this study are in the central Pyrenees, 9 located in Spain and 2 in Andorra (Fig. 1). The lowest elevations for the ski slopes typically range from 1500 to 1700 m a.s.l. Only 30% of them have skiable areas higher than 2500 m, with 2800 m being the maximum. Fig. 2 shows data for the study ski stations based on three criteria: length of ski slopes (km), the number of ski slopes, and the capacity to displace skiers per hour. The largest station is Grandvalira, which has 210 km of skiable area, the greatest number of ski slopes (118), and the greatest capacity (100.000 skiers per hour). Apart from four relatively large stations, the remainders have 45–79 km of ski slopes, and capacities of 15.000–25.000 skiers per hour. The three small stations the ski slopes range from 6 to 34 km in length, and the capacity ranges from 5000 to 13.000 skiers per hour.

3. Methods

3.1. Data

For each ski resort for the period 1960–2006 we calculated the number of days per season (from December to April) on which several climate or snow depth thresholds considered to define skiability were exceeded. The analysis involved the middle and