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Impact of Large-scale Climatic Oscillations on Snowfall-related Climate Parameters in the World's Major Downhill Ski Areas: A Review

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Skiers are passionate about finding the best snow conditions. Snow conditions in thousands of ski resorts around the world depend mainly on natural snowfall, particularly in the case of backcountry skiing. In various mountain ranges popular among skiers, snowfall is strongly linked to large-scale climatic oscillations. This paper reviews existing information on the impacts of several of these phenomena, such as the El Niño–Southern Oscillation, North Atlantic Oscillation, and North Pacific Index, on snowfall-related climate parameters in the world's major ski areas. We found that in each of the studied areas, one or more large-scale climatic oscillations affected snowfall-related climate parameters. Understanding the predictability of such oscillations is high on the climate research agenda. If this research leads to improved predictability in the coming years, this could be combined with the knowledge summarized in our paper on the relationships between climatic oscillations and snow-related parameters to provide useful information for winter sports and other snow-related fields.

Keywords: *Large-scale climatic oscillations; predictability; snowfall; ski areas; global overview.*

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Introduction

In many economic sectors, it is recognized that interannual climate variability is at least as important as long-term climate change for practical issues (Mogaka et al 2006), such as drought management (D'Arrigo and Smerdon 2008), food production (Rosenzweig and Hillel 2008), and hurricane losses and insurance (Pielke et al 2008). For ski resorts, the amount of snow, length of snow cover periods, number of snowfall events, and consistency of the snow pack are of crucial importance, because these characteristics are known to determine the suitability of snow for sports such as skiing (Laternser and Schneebeli 2003; Marty 2008). In the last few decades, the importance of artificial snowmaking has increased, mainly due to climate change and the growing demands of skiing tourists (Elsasser and Messerli 2001; Scott et al 2003; Rixen et al 2011). An improved understanding of the impacts of climate variability on snowfall could be beneficial for management purposes in skiing-related businesses and for skiers themselves to understand where there is the most potential for good snow.

Various studies exist on regional and local scales on how different large-scale climatic oscillations affect snowfall, winter precipitation, and temperature (eg Brown and Goodison 1996; Aizen et al 2001; Quadrelli et al 2001; Sturman and Wanner 2001; Jhun and Lee 2004; Scherrer et al 2004; Scherrer and Appenzeller 2006; Masiokas et al 2006; Durand et al 2009a, 2009b; Bao et al 2011; Purdie et al 2011a, 2011b). On the global scale, several studies examine relationships between climate variability, temperature, and precipitation (eg Ropelewski and Halpert 1987, 1989, 1996; Kiladis and Diaz 1989; IPCC 2012) or hydrological aspects such as river discharge (eg Dettinger and Diaz 2000; Dettinger et al 2000; Ward et al 2010) or drought (eg Rosenzweig and Hillel 2008 and references therein). However, to our best knowledge, there exists no global overview related to snowfall or snow depth.

The objective of this study is thus to examine the relationship of parameters important for snowfall with large-scale climatic oscillations in the major downhill skiing areas worldwide. The study is based on a comprehensive summary of the existing scientific literature.

Study area and climatic phenomena

Skiing regions

This study focused on the following ski areas (in alphabetical order): Alps (Europe), Andes (Argentina and Chile), Canada (west coast), Japan (Hokkaido), New

TABLE 1 Main skiing regions.[a)]

Ski region	Latitude	Mean altitude (approximate range)	Mean winter temperature, 1960–1990 (°C; high/low)	Mean winter precipitation, 1960–1990 (mm; high/low)
Alps, Europe	44–47°N	1770 (400–4530)	−3.2 (−13.3/+5.1)	460 (180/1130)
Andes, Argentina and Chile	33–41°S	2090 (520–5450)	+1.2 (−12.8/+7.4)	560 (180/1200)
Canadian west coast	49–55°N	1570 (200–3880)	−7.2 (−14.2/+4.4)	320 (120/1100)
Hokkaido, Japan	42–44°N	690 (50–2120)	−6.3 (−13.9/−1.0)	470 (330/700)
South Island, New Zealand	41–45°S	1150 (100–3170)	+2.0 (−5.3/+6.9)	1010 (300/1930)
Scandinavia	58–70°N	660 (10–2290)	−7.6 (−15.2/+2.7)	330 (130/1380)
US west coast	35–49°N	2090 (200–4320)	−4.4 (−12.6/+10.7)	300 (40/1980)

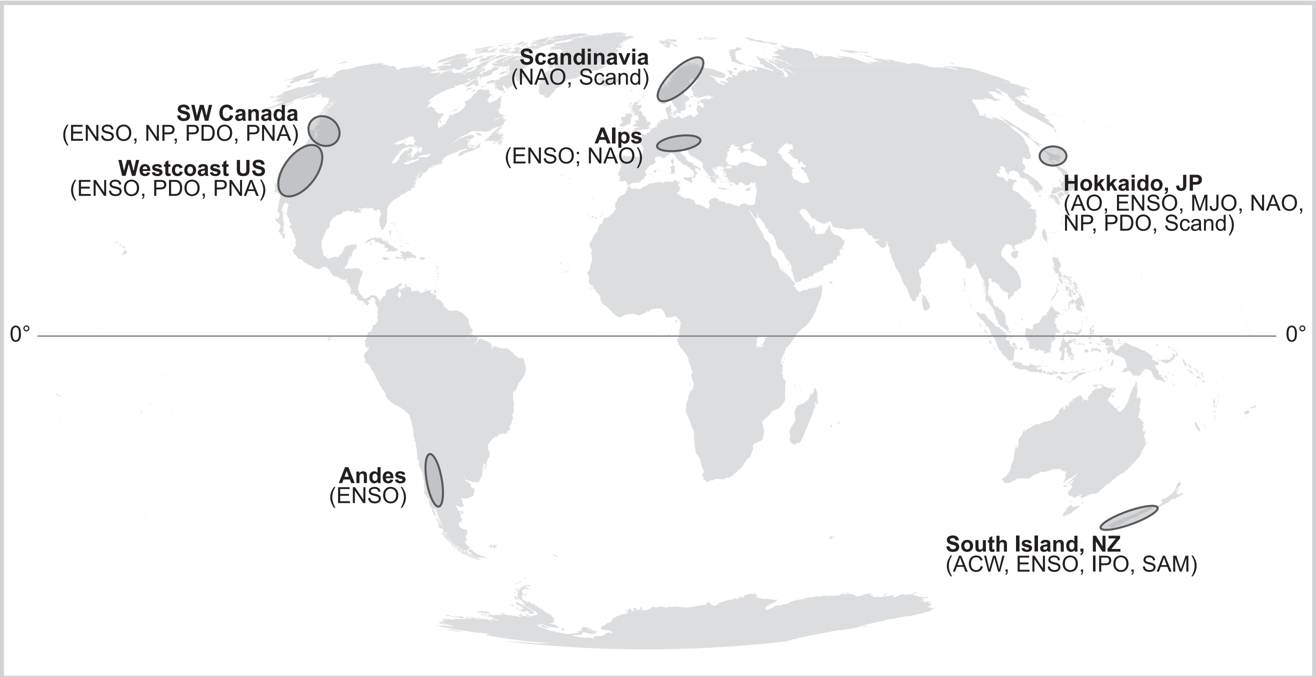
[a)]Wintertime lasts from November to March in the Northern Hemisphere and from May to September in the Southern Hemisphere. Values are averages for the whole mountain range in which the main skiing resorts are located.

Sources: For altitude data, digital elevation model generated by USGS, 2001; for temperature and precipitation, WorldClim v1.4, Hijmans et al 2005.

Zealand (South Island), Scandinavia (Norway and Sweden), and the United States (west coast). The main characteristics of these skiing regions are summarized in Table 1, and their locations are schematically mapped in Figure 1.

We selected the preceding listed mountain ranges to focus on the largest ski areas, where most skiing resorts are located and the largest numbers of people are skiing (the Alps account for 46% of total skier visits, the United States 15%, Japan 11%, Canada 5%, and Scandinavia 4%; Vanat 2011), and the two main skiing areas in the Southern Hemisphere (the Andes, with 0.8% of total skier visits, and New Zealand's South Island, with 0.4%). Although the latter two regions are less important in

FIGURE 1 Locations of skiing regions and large-scale climatic oscillations. See Table 2 for definitions of climatic oscillations and Table 3 for their impacts on snowfall-related climate parameters. (Map by authors)



terms of the number of skiers, they are the most important skiing regions in their hemisphere. In the United States and Canada, we concentrated on the west coast skiing areas, where the largest ski resorts of both countries exist (eg Vanat 2011). We intentionally excluded many medium-size skiing areas, such as the Tatra Mountains, Caucasus Mountains, Pyrenees, various East Asian areas, and northern Finland, to focus our study. Medium-size and small skiing areas would make a valuable subject for future research.

There are large differences between regions in terms of the amount of literature available in English on the topic. These differences do not necessarily imply differences in the issue's complexity among regions.

Large-scale climatic oscillations

The term *climate variability* refers to natural fluctuations in climate (in averages and extremes) about the mean on all temporal and spatial scales beyond individual weather events (Parker et al 2007). Earth's climate is inherently variable from the seasonal to the millennial scale, the latter illustrated by repeated glacial and interglacial periods. For most management purposes, variability influencing extremes on annual to decadal timescales is especially relevant (McPhaden et al 2006). This includes internal variability through large-scale oceanic–atmospheric oscillations. The most well known of these is the El Niño–Southern Oscillation (ENSO), which affects climate worldwide (Peixoto and Oort 1992). There are, however, many other large-scale oceanic–atmospheric oscillations affecting regional weather, as discussed in this section. In this study, we refer to these collectively as large-scale climatic oscillations.

The intensities and expressions of these oscillations are typically described by indices showing the differences in expression of a certain atmospheric or oceanic parameter, such as sea level pressure (SLP) or sea surface temperature (SST), in a region. For example, the phase and strength of ENSO is commonly represented using indices of standardized anomalies of SLP or SST between locations in the eastern and western Pacific. However, the impacts of ENSO on meteorological parameters such as temperature, rainfall, and snowfall are not restricted to this Pacific region; rather, they can be seen around the world. These temporally correlated occurrences of climate anomalies and meteorological parameters in far-removed regions are called teleconnections (eg Panagiotopoulos et al 2002; Liu and Alexander 2007).

A variety of indices have been created for different phenomena depending on the methodology and dataset used for their evaluation (Barnston and Livezey 1987; Rogers 1990; Panagiotopoulos et al 2002; Stenseth et al 2003). Given this variety, we must separate the physics of a phenomenon from its index. A comprehensive introduction to this issue and most large-scale oscillations mentioned in this study, as well as the problem of diversity of indices for one phenomenon, are provided by Panagiotopoulos et al (2002) and Stenseth et al (2003). The latter also discusses several general pros and cons for the use of climate indices and the problem of nonstationarity of relationships between local weather and indices.

Our study includes the main large-scale climatic phenomena reported in the literature affecting snowfall, winter precipitation, or temperature in the study areas. Because several indices describe most climatic phenomena, this paper refers to the phenomena themselves rather than to individual indices, except for the North Pacific (NP) index. Throughout the text, abbreviations of each phenomenon with + and − indicate the positive and negative or high and low phases, respectively, as reported for the indices of the phenomenon used in the cited studies (Table 2 and Figure 2). Please note that the further differentiation in the neutral phase of ENSO and its extremes, El Niño (La Niña) for relatively long-lasting warm (cold) anomalies, depends on the thresholds used in the respective studies to which we refer. The phenomena are listed and briefly described in Table 2. More detailed descriptions are available in the cited literature.

Literature review

This section reviews the current understanding of the impacts of the large-scale climatic oscillations described previously on snowfall (or related weather conditions, such as winter temperature and winter precipitation) in the regions under study.

Alps

Alpine climatology is diverse and complex due to the region's orography and position among different climatic regimes: continental, Atlantic, Mediterranean, and polar climatic regimes interact in many ways with the mountainous topography (Wanner et al 1997; Quadrelli et al 2001; Beniston 2005). Furthermore, at high altitudes, the amount of snow depends mainly on the amount of precipitation, while at low and middle altitudes, temperature is the dominating factor (Scherrer et al 2004; Durand et al 2009b).

An overall pattern of a negative correlation for snowy winters with the North Atlantic Oscillation (NAO) is found by Henderson and Leathers (2010) for the whole of central Europe, including the Alps. While some authors state that there is a tendency toward lower precipitation during months with NAO+ compared to months with NAO− (Quadrelli et al 2001; Beniston and Jungo 2002), some others found no clear relationship for the Alps as a whole (Bartolini et al 2009; Durand et al 2009a). Nonetheless, there seems to be a negative relationship between NAO and snow depth (Durand et al 2009b). In a study examining evidence over the last 500 years, Casty

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TABLE 2 Definitions of large-scale climatic phenomena and corresponding abbreviations. (Table continued on next page.)

Abbreviation	Name	Description	Time scale	References
ACW	Antarctic Circumpolar Wave	An eastward propagating wave, together with the circumpolar flow, SST, SLP, and meridional surface wind, in the Southern Ocean with 2 wavelengths encircling the globe (global zonal wave 2). Average propagating speed is 45° longitude per year, so ACW takes 8–10 years to circle the globe, and every 4–5 years the same kinds of effects take place. There is a discussion about whether the ACW is a self-contained phenomenon or whether the observed patterns are an ENSO-induced quasistationary wave train of anomalies.	8–10 years	White and Peterson 1996; White and Cherry 1999; Park et al 2004
AO	Arctic Oscillation	Also Northern Annular Mode (NAM). Zonal/annular SLP pattern around the northern pole with two centers of action, in the Atlantic and Pacific basins, which reflect the interplay of the strength of the polar vortex and the surrounding wind systems.	Annual	Ambaum et al 2001; Thompson and Wallace 2001; Ogi et al 2004
ENSO	El Niño–Southern Oscillation	Coupled interacting atmospheric–ocean system. The atmosphere–wind–pressure component, the Southern Oscillation, is the interannual alternation of SLP in the Indo-Pacific region. El Niño is associated with positive departures in SST indices (or negative departures in SLP indices) of ENSO in which trade winds and Walker circulation are weakened, while negative departures in SST indices (positive departures in SLP indices) are associated with cool La Niña. Depending on the index used, there are different thresholds to distinguish El Niño and La Niña from the neutral phase. ENSO is the most uniform interannual climate variability after the annual cycle.	Annual	Rasmusson and Wallace 1983; Trenberth 1997; Fedorov and Philander 2000; Collins et al 2010
IPO	Interdecadal Pacific Oscillation	Similar to PDO but for the whole Pacific Basin and without subdecadal frequencies. Modulates the teleconnections of ENSO.	Decadal	Salinger et al 2001; Folland et al 2002a, 2002b
MJO	Madden-Julian Oscillation	SLP wave perturbating; also the upper zonal winds and atmospheric convection and moving eastward (in the opposite direction of the trade winds) through the parts of the Indian and Pacific Ocean with warm SST, bringing anomalous rainfall periods of 30–90 days. Dominant intraseasonal mode of large-scale tropospheric variability in the tropics. Important component regulating the strength of tropical monsoons, but also affects mid- and even high latitudes.	Seasonal	Madden and Julian 1994; Vecchi and Bond 2004; Zhang 2005
NAO	North Atlantic Oscillation	Highly correlated with AO, but restricted to the Atlantic Basin. Results from atmospheric–oceanic interactions. NAO is a hemispheric, meridional oscillation in atmospheric pressure with centers of action near Iceland and over the subtropical Atlantic; that is, there is a clear north–south dipole structure.	Annual	Thompson and Wallace 2001; Wanner et al 2001; Hurrell and Deser 2009

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TABLE 2 Continued. (First part of Table 2 on previous page.)

Abbreviation	Name	Description	Time scale	References
NP	North Pacific Index	Highly negatively correlated with PNA, but focused on the northern Pacific Basin. Highly negatively correlated with PDO. Defined by November–March SLP anomalies in the North Pacific (30°–65°N, 160°E–140°W). Has periods of more than 2 to 3 decades with predominantly positive or negative values but also higher frequency variability. Represents the strength of the Aleutian Low in winter.	Annual to decadal	Trenberth and Hurrell 1994; Deser et al 2004; Jhun and Lee 2004
PDO	Pacific Decadal Oscillation	SST pattern varying on an interdecadal time scale (~20–30 years) in the Pacific Basin north of 20°N with more or less consistent positive or negative values during an epoch. PDO is highly positively correlated with ENSO, so it is thought of as an ENSO-like interdecadal climate variability, a kind of envelope of interannual ENSO variability, or a modulating force for ENSO.	Decadal	Mantua et al 1997; Minobe 1997; Gershunov and Barnett 1998
PNA	Pacific North American Oscillation	Can be understood as one of the 2 poles of AO, together with the NAO. Similar to NAO, PNA has a north–south orientation on the eastern part of the Pacific Basin, with 4 centers of action near Hawaii, the North Pacific Ocean, Alberta, and the Gulf Coast region of the United States.	Annual	Wallace and Gutzler 1981; Ambaum et al 2001; Hurrell and Deser 2009
SAM	Southern Annular Mode	Also Antarctic Oscillation (AAO) or high-latitude mode. Reflects the SLP alternation between Antarctica and the surrounding 40–50°S wind belt. Analogue to NAM at the southern pole but with even more zonal characteristics due to fewer hindering landmasses.	Annual	Gong and Wang 1999; Thompson and Wallace 2000; Gupta and England 2006
Scand	Scandinavian Pattern	Former Eurasian type 1 pattern with 3 centers of action: the dominant one over the Scandinavian peninsula and 2 opposite-signed ones over northwest China–Siberia and over the northeastern Atlantic.	Annual	Barnston and Livezey 1987; Bueh and Nakamura 2007; Popova 2007

et al (2005) found NAO+ to be related to lower precipitation and relatively higher temperatures for intermittent periods, which corresponds well with earlier findings (Beniston 1997; Wanner et al 1997).

In addition to the influence of different scales, data, time windows, and methods, Casty et al (2005) propose another explanation for the different findings. They argue that the Alps are situated in a band of varying influence of NAO. This fits well with the known change of sign of correlations between NAO and winter precipitation around the latitude of the Alps and the understanding of the region as a transition zone of NAO's influence (Bartolini et al 2009). Other studies attempt to subdivide the NAO into a polar–Mediterranean component and an Azores–Iceland component (Kodera and Kuroda 2004; Efthymiadis et al 2007). The polar–Mediterranean component would explain more of the high Alpine winter temperature variability.

Quadrelli et al (2001) found no statistically significant relationships between ENSO and Alpine winter climate variables. However, there are findings for intermittent ~5-month lagging negative correlations between cold ENSO events and precipitation and positive correlation between cold ENSO events and pressure anomalies from January–March in the Greater Alpine Region (Efthymiadis et al 2007). While the relationship between ENSO and precipitation was found to be more pronounced for cold ENSO phases, in the case of November–January temperature the relationship was more pronounced for the warm ENSO phase, especially for El Niño events. Efthymiadis et al (2007) found periods with alternating correlations between temperature and ENSO. The relationship might furthermore be influenced by the tendency to invert El Niño's correlation with occurrence of NAO+ from positive in November–December to negative in January–March (and the other way around for La Niña with occurrence of NAO−; Moron and Plaut 2003).

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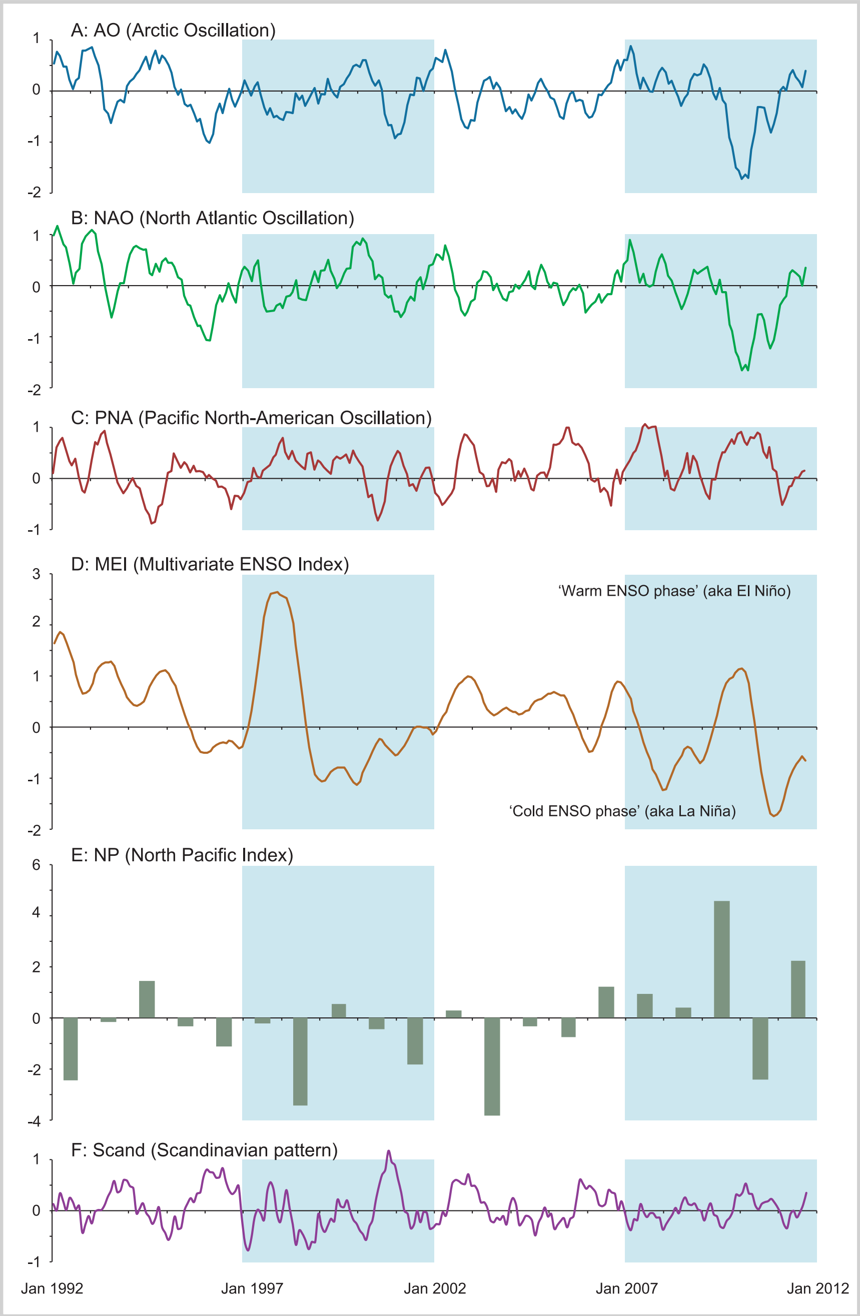
FIGURE 2 Selected intra-annual climatic oscillations, January 1992–December 2011. (A) AO; (B) NAO; (C) PNA; (D) Multivariate ENSO index; (E) NP; (F) Scand. (Sources: AO [CPC 2012a]; NAO [NCAR 2012a]; PNA [CPC 2012b]; MEI [NOAA 2012]; NP [NCAR 2012b]; Scand [CPC 2012c]). Data are presented as 7-month moving averages, except NP data, which are presented as November–March anomalies based on the 1925–1989 mean; the shaded areas separate 5-year periods.



Chilean–Argentinean Andes

Masiokas et al (2006) found snow accumulation in the central Andes to be positively related to El Niño but found no clear relationship with La Niña. The correlations that they found between snowfall and annual amount of rainfall in central Chile fit well with the known positive correlation of precipitation with El Niño during the Southern Hemisphere winter (June–August) (Waylen and Caviedes 1990; Montecinos and Aceituno 2003). An important factor for this phenomenon is El Niño-related blockings and positive height anomalies in the Amundsen and Bellingshausen Seas region; together with a weakened subtropical Pacific anticyclone, this leads to a northward shift of the westerlies (Renwick 1998; Montecinos and Aceituno 2003; Masiokas et al 2006). These moisture-laden air flows lead to precipitation in the mountain ranges of the Andes (Montecinos and Aceituno 2003; Masiokas et al 2006). Garreaud (2009) describes positive

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(negative) relationships between El Niño (La Niña) and precipitation and with surface air temperature during the Southern Hemisphere winter.

Canadian west coast

In this region, the Pacific North American Oscillation (PNA) has the strongest influence and is inversely related to snow cover extent (Brown and Goodison 1996). This is supported by findings of negative (weak positive) correlation of winter temperature (precipitation), with NP resulting in lighter than average 1 April snowpack water equivalent (SWE) anomalies for low NP index (Moore and McKendry 1996). NP is used here as an anticorrelated measure of the strength of PNA (Table 2). At the same time, NP is highly negatively correlated with the Pacific decadal oscillation (PDO). A PDO-like step shift in SWE anomalies is found in southwest British Columbia, especially near the coast and weaker for increasing latitudes (Moore and McKendry 1996). In southwest British Columbia, NP is found to be positively correlated with snowfall and SWE, and negatively correlated with temperature (Moore 1996). Rodenhuis et al (2009) state that there is a positive relationship between PDO+ and winter temperature along the coast of British Columbia and in the northern regions, while PDO− is related to negative winter temperature anomalies only in some parts of the southern coastal region. For winter precipitation there is no clear relationship, but for SWE a negative correlation exists with PDO in southern British Columbia. In another study in southeast British Columbia, SWE is negatively correlated with PDO (McCabe and Dettinger 2002). Whitfield et al (2010) found PDO to be negatively correlated with snow accumulation and positively correlated with date of snowmelt. They give a comprehensive review of the effects of PDO, and the related NP and PNA, on British Columbia's winter climate. Their findings are consistent with those mentioned previously.

El Niño associations are variable and less strong than PNA associations but are likewise negatively related (Brown and Goodison 1996). However, there are also other findings of increasing SWE and negative winter temperature anomalies for La Niña and decreasing SWE and positive winter temperature anomalies for El Niño (Rodenhuis et al 2009). Hsieh and Tang (2001) found that, in the Columbia Basin, PNA and El Niño are both positively correlated with SWE anomalies, while La Niña is negatively correlated with SWE anomalies. The strength of the correlations decreases in the following order: PNA+, La Niña, El Niño, and PNA−. Shabbar (2006) states that especially strong El Niño events lead to a well-developed PNA via a standing Rossby wave, which in turn leads to comparatively warm and dry winters in southern Canada and reduced snowfall amounts in the western area. There are more and longer warm spells and fewer cold spells in winter in southwest Canada during El Niño compared to La Niña, and in general fewer cold and more warm days (Shabbar and Bonsal 2004). Groisman et al (1994) found a negative relationship between snow cover extent and El Niño in southern Canada. The ENSO effects in winter in southwest British Columbia are enhanced by PDO with the strongest interaction if both are in phase (Kiffney et al 2002). Fleming and Whitfield (2010) found the same in-phase effect for winter temperature but for a wider geographical region throughout the whole of British Columbia. Out-of-phase relationships are found to correlate with weaker or reversed winter temperature anomalies (Bonsal et al 2001).

Hokkaido, Japan

Relatively cold (warm) winter temperatures in Japan are associated with strong (weak) East Asian winter monsoon (EAWM) (Jhun and Lee 2004). In turn, the EAWM is positively correlated with autumn snow cover in Siberia, China, and eastern Russia and the strength of the Aleutian Low and Siberian High. It is furthermore negatively correlated with the NP on an annual timescale and with the Arctic Oscillation (AO), NP, NAO, and PDO on a decadal timescale (Jhun and Lee 2004). However, Jhun and Lee (2004) found no correlation between NP and PDO. An influence of EAWM by AO through the Siberian High on a decadal timescale is postulated (Gong et al 2001; Jhun and Lee 2004). NP is positively correlated with temperature in Japan (Trenberth and Hurrell 1994). The AO is positively correlated with temperatures in Eastern China and negatively correlated with Siberian High, while Scandinavian Pattern (Scand) is negatively correlated with temperatures in Eastern China and positively correlated with the Siberian High (Gong et al 2001). This fits with findings of enhanced incidence rates of cold winter events in East Asia during AO− (Thompson and Wallace 2001). In Hokkaido, winter precipitation is negatively associated with the Siberian High (Aizen et al 2001). Phase 7 of the Madden−Julian Oscillation (MJO) in the La Niña phase is found to cause very strong winters in Japan by enhancing the winter monsoon (Moon et al 2011).

New Zealand South Island

New Zealand's South Island climate is much determined by its position in the subpolar westerlies and an abrupt change from sea to high mountains, which leads to a steep precipitation gradient from up to 6000 mm yr^{-1} on the western part of the island's Southern Alps to 600–1500 mm yr^{-1} on the eastern part (Sturman and Wanner 2001; Clare et al 2002; Ummenhofer and England 2007). Most skiing areas are situated eastward from the mountain ridge. Stronger westerly and southwesterly winds and troughing regimes during El Niño enhance snow deposition in the Southern Alps, whereas stronger northeasterly winds and blocking regimes during La Niña reduce snow deposition in the Southern Alps (Gordon 1986; Kidson 2000; Sturman and Wanner 2001; Purdie et

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al 2011a, 2011b). A tendency to a similar but nonsignificant relationship of wind and glacial mass balance, respective to end-of-summer snowlines on New Zealand's South Island glaciers, is reported by Clare et al (2002). ENSO teleconnections are observed to be stronger during the interdecadal Pacific oscillation (IPO)+ (Salinger et al 2001).

According to White and Cherry (1999), high temperature anomalies over the South Island occur with the warm SST-part and meridional surface wind anomalies of eastward propagating Antarctic Circumpolar Wave and at the same time a negative but clearly weaker relationship for winter precipitation. There is, however, a discussion about whether the Antarctic Circumpolar Wave exists. Park et al (2004) suggest that the presumption of stationary ENSO wave signals is a more reliable explanation for eastward propagating anomalies in the Southern Ocean. In a more recent study, Ummenhofer and England (2007) prefer to explain rainfall anomalies over the South Island with the circumpolar Southern Annular Mode (SAM). They found SAM+ years corresponding with weakened westerlies, strengthened northeasterly flow, and reduced precipitation throughout the island except for in the northernmost region, which stands out for its increased precipitation. For SAM−, the relationships tend to be reversed but more concentrated on the western part of the Alps—in other words, a reversed but weaker relationship exists for the main ski areas east of the Alps. In SAM−, the exceptional northernmost part with distinct low precipitation is somewhat larger than in the case of SAM+. The wind–snow relationship for SAM is consistent, only phase inverted, with the one described previously for ENSO (Purdie et al 2011b). End-of-summer snowlines are inversely related to the surrounding SST of the South Island and tend to be inversely related to SAM (Clare et al 2002). Overall, SAM is found to be more dominant than ENSO for the South Island, with the main areas of ENSO influence being mostly removed from the main skiing areas (Ummenhofer and England 2007). In the same study, warm (cold) SST anomalies are found around the South Island for anomalously dry (wet) years.

The main difference in average precipitation of dry and wet years takes place in the Southern Hemisphere spring (August–October) and autumn (March–May; Ummenhofer and England 2007). Hence, only the months of May, August, and September contribute to winter precipitation as it is defined in this study.

Renwick and Thompson (2006) found positive relationships between daily maximum temperature and SAM, except for in the eastern and northeastern part, and negative relationships between daily rainfall only in the most western part of the South Island. Those findings agree with positive monthly temperature and negative monthly precipitation anomalies for SAM+ (Gillett et al 2006). Kidston et al (2009) found positive relationships between temperature and SAM in the winter (June–August) for the whole South Island. For winter rainfall, they found a positive correlation with SAM in the most western part of the South Island and a negative correlation on the eastern and northern side. Based on climate reanalysis data, Gupta and England (2006) reported positive relationships between SAM and monthly SST and negative (in the northern part of the South Island, weaker with confidence levels below 90%) relationships with monthly precipitation.

Scandinavia (Norway and Sweden)

Winter precipitation is positively correlated with NAO in northern Sweden and along the coast of Norway (Wanner et al 2001; Uvo 2003). This finding is affirmed by the positive relationships between NAO and precipitation and temperature that Beranová and Huth (2008) found for the whole of Scandinavia and by the findings of Chen and Hellström (1999) that there is a positive correlation between NAO and winter temperature in Sweden, diminishing toward the north and east. The strengthened westerlies transport moist air from the Atlantic, which precipitates along the coastline and the Scandinavian mountain range (Uvo 2003). Mysterud et al (2000) found positive correlations between NAO and both temperature and precipitation in the western part of southern Norway. Because of the high northern latitude, winter temperatures in that region are often ~0°C, and altitude is an important determining factor. They found NAO to correlate negatively (positively) with snow depth below (above) ~400-m altitude.

Bueh and Nakamura (2007) found negative correlation between winter precipitation and Scand for the Scandinavian region, mainly along the Norwegian coast, due to weakened westerlies as they are shifted toward the south. However, Beranová and Huth (2008) state that there is no such correlation, except for at one station in Sweden, where there is negative correlation with precipitation, and the four most northern stations in Scandinavia, where there are positive relationships between Scand and temperature.

US west coast

The literature describes correlations between El Niño and dry and warm winters and La Niña and snowy winters for the northwest United States, and correlations between El Niño and wet and cool snowy winters and La Niña and less snowy winters for the southwest United States (Cayan 1996; Cayan et al 1999; Kunkel and Angel 1999; McCabe and Dettinger 2002; Patten et al 2003; Bark et al 2010). McCabe and Dettinger (2002) found PDO to be negatively correlated with SWE data for 1 April in the northwestern United States. This is consistent with general negative correlations between PDO and snow depth in the Pacific Northwest, positive correlations between PDO and winter air temperatures, and negative correlations between PDO

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and precipitation anomalies (Mantua et al 1997). Strong Aleutian Lows and high pressure over the western United States in the PNA+ phase are found to be correlated with low snow depth in that region (Cayan 1996; McCabe and Dettinger 2002). This is consistent with findings of positive temperature anomalies and corresponding decreasing snow depths related to PNA+ (Ghatak et al 2010; Bao et al 2011).

An explanation for different findings or expressions of patterns might be the interaction of PDO with ENSO. During the high (low) phase of PDO the effects of El Niño (La Niña) are strengthened, especially on the west coast. If the phenomena are in an opposite phase in that sense, the effects are dampened or might even vanish (Gershunov and Barnett 1998). The authors in the former study refer to the PDO as the North Pacific Oscillation.

Discussion and conclusions

The previous section provides a comprehensive overview of the influence of large-scale climatic oscillations on snowfall and related climate patterns in the world's main skiing regions. Because of the vast amount of literature and ongoing discussions in the tangent fields, including contradicting findings on the influence of various phenomena, knowledge in some regions remains somewhat fragmented. We believe, nevertheless, that the findings provide a valuable summary of the current understanding of the issue.

Skiing conditions

A summary of findings, showing the main relationships between various climate phenomena and snowfall or related climate parameters (winter temperature, precipitation, or both) in each studied region, is presented in Table 3. The terms for the effects listed in Table 3 are taken from the literature described previously. We decided to list the unmodified terms because while the parameters of snow, snow depth, snow cover, or snowfall are related, they are not the same. Furthermore, the question of which combination of temperature and precipitation leads to a number of days with a suitable amount of snow on the ground for skiing is highly site specific.

For example, Durand et al (2009a) show the influence of latitude on snow in the French Alps: there are ~60 more days with snow on the ground in the northernmost massifs compared to in the southernmost massifs at low (1200 m) and middle (1500 m) altitudes. Mysterud et al (2000) found increasing snow depths at higher altitudes at the coast compared to inland, with a tendency for the rain- or snowline to occur at lower altitudes while moving to the north.

Unfortunately, to the best of our knowledge, there is no global dataset or map of average winter snowline, snow cover, and depth or similar information that could be used as a reference point to scale the relationships with the large-scale oscillations collected in this study to a certain region. This shortcoming might have a positive side: it prevents us from presenting overly rough estimates, because there is a high natural diversity within the study areas due to aspects such as orography, orientation, and distance to the sea.

The scale of this study is outlined in Table 1. For specific sites, the effects described in Table 3 should be seen as general tendencies in that region.

Correlations between oscillations

This paper reported correlations between individual climatic oscillations and snowfall and related climate variables as stated in the reviewed literature. The choice of phenomena and indices to include in the review depends heavily on the preferences and approaches of the reviewed articles. This study does not consider correlations, interactions, or overlapping definitions among different phenomena. For example, there is a clear overlap between NAO and AO, because of which most findings are valid for both phenomena (Ambaum et al 2001; Wanner et al 2001; Hurrell and Deser 2009), and PNA is sometimes called an "extratropical arm of ENSO" (Hurrell and Deser 2009).

Climate variability and predictability

We have shown that there are clear correlations between snow-related parameters and several large-scale climatic oscillations in many of the world's major skiing regions. To maximize the benefit of such knowledge for users (such as skiers and ski resort managers), these findings should be linked to information on the predictability of the different oscillations. This predictability at seasonal to decadal scales is a top research priority in the field of climate modeling, for example, as part of the Coupled Model Intercomparison Project (Taylor et al 2012). Operational ENSO forecasting, such as the ENSO forecast of the Climate Prediction Center of the National Oceanic and Atmospheric Administration, has been one of the success stories of climate research (Collins 2002). This has contributed to the effectiveness of seasonal climate forecasts, especially in tropical regions but also in midlatitude regions in which ENSO teleconnections are seen (Barnston et al 2010).

The predictability of other large-scale climatic oscillations is an important topic (Lau and Waliser 2012). Of particular interest in Northern Hemisphere skiing regions is the predictability of AO-NAO. While several studies suggest that AO is a result of intrinsic atmospheric dynamics or chaotic behavior and therefore unpredictable (eg Seager et al 2010; Jung et al 2011), Cohen and Jones (2011) suggest that it may be a relatively easily predicted phenomenon. They base this finding on a predictive index (derived from antecedent observed snow cover) that explains close to 75% of the variance of winter AO. Research also abounds on other oscillations (Sobolowski

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TABLE 3 Effects of large-scale climatic phenomena. See Table 2 for definitions and abbreviations of each phenomenon. EAWM, East Asian winter monsoon; SWE, snowpack water equivalent. (Table continued on next page.)

Region	Phenomenon[a]	Effect[b]
Alps, Europe	NAO	Snowfall, snow depth, ~ precipitation −
	NAO+	~ temperature +
	ENSO	~ temperature changing relationship
	Cold ENSO	~ precipitation −
	Interaction of ENSO and NAO	See text
Andes, Chile and Argentina	El Niño	Snowfall, precipitation (winter: June–August) +
Canadian west coast	NP	Temperature − SWE, snowfall, ~ precipitation +
	PNA	Snow cover extent −
	PDO	Earlier snowmelt, ~ temperature + SWE, snow accumulation −
	El Niño	Temperature + Snowfall, precipitation, snow cover extent, SWE −
	La Niña	SWE + Temperature −
	Interaction of ENSO and PDO	Enhanced effects if in phase; see text
Hokkaido, Japan	AO, NAO, NP, PDO	~ temperature (decadal time scale) + (* EAWM) ~ precipitation (decadal time scale) − (* Siberian High)
	NP	Temperature (annual time scale) + (* EAWM)
	Scand	~ temperature − Precipitation + (* Siberian High)
	AO	Temperature + (* Siberian High) Precipitation − (* Siberian High)
	La Niña and MJO (phase 7)	Temperature − (strong winter; * EAWM)
South Island, New Zealand[c]	El Niño	Snowfall +
	La Niña	Snowfall −
	IPO+	Enhances ENSO teleconnections
	ACW (SST+)	Temperature + Precipitation −
	SAM	~ precipitation − ~ temperature +
Scandinavia	NAO	Precipitation, temperature, snow depth +
	Scand	~ precipitation −
US west coast	PNA+	Snow depth − Temperature +
	PDO+(−) & El Niño (La Niña)	ENSO effects strengthened
	PDO−(+) & El Niño (La Niña)	ENSO effects weakened

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TABLE 3 Continued. (First part of Table 3 on previous page.)

Region	Phenomenon[a]	Effect[b]
US northwest coast	El Niño	Precipitation − Temperature +
	La Niña	Snow +
	PDO	Snow depth, precipitation − Temperature +
US southwest coast	El Niño	Temperature − Precipitation, snow +
	La Niña	Snow −

[a)] + and − in "phenomenon" column indicate the positive and negative phases, respectively. If phenomenon is in positive or negative phase, + or − in "effect" column indicates positive or negative anomalies. If phenomenon is without phase specification, + or − in "effect" column indicates positive or negative relationship.
[b)] Use of symbols: ~ in front of the abbreviation of an effect indicates that the effect is not strongly established, that there are no consistent findings throughout the regions (some authors find a relationship while others do not), or that the findings are not for the specific region but for a larger surrounding area (eg East Asia and Japan); * means inferred from the relationships with the quoted climate element described in the corresponding paragraphs.
[c)] Note that there are differences between the Western Alps and the Eastern part of NZ's South Island; and the Northern part is very particular.

and Frei 2007; Randall et al 2007; Lau and Waliser 2012). A full review is beyond the scope of this paper, but it is clear that where predictability of climatic oscillation is improved, the link to the correlations with snow-related parameters could be of benefit to the ski industry.

Future research directions

As the publically available daily snowfall data at the global scale (eg NOAA 2005) are rather sporadic, and have varying quality for most analyzed regions, we needed to rely only on the documented studies in this article. One option for further research would be to systematically test all large-scale climatic oscillations impacting the snowfall in each area using global reanalysis data (eg ERA40 [reanalysis data by European Centre for Medium-Range Weather Forecasts] or CRU [reanalysis data by Climate Research Centre of University of East Anglia]) or using the snow component of existing hydrological models to simulate snowfall. This could then be correlated with the observed indices. However, global hydrological models mostly use a 0.5° resolution that is rather coarse for the mountain areas where snowfall is often spatially heterogeneous. The 5′ versions of global hydrological models (eg a new version of the WaterGAP model that is being developed) could already provide an adequate resolution for this purpose. Another option to validate, scale, or do both to our findings might be the estimation of the median winter snowline (Hantel and Maurer 2011) or approaches via remote sensing data (Parajka et al 2010).

Although there are some indications on how the different large-scale climatic oscillations are impacting the snowfall together (eg IPO+ enhances ENSO impact on snowfall in New Zealand South Island; Table 3), in many regions those interactions are not clear. In those areas, further regional studies are required.

The oscillations considered in this study are not the only phenomena that impact snowfall. Other large-scale drivers of climate, such as ocean currents (Qiu and Miao 2000; Di Lorenzo et al 2008), the interaction of different atmospheric spheres (Baldwin and Dunkerton 2001), the quasibiennial oscillation (Baldwin et al 2001), or extraterrestrial factors (such as solar activity), might also impact snowfall-related climate parameters. Furthermore, the feedback loops of Eurasian snow cover are known to affect global oscillation phenomena (Cohen and Entekhabi 1999; Gong et al 2002; Bojariu and Gimeno 2003; Cohen and Saito 2003). On a smaller scale, phenomena such as regional microclimatology and characteristic weather regimes (such as blocking for the Alps) finally determine the actual weather conditions (Wanner et al 1997; Quadrelli et al 2001). These large- and small-scale phenomena are, however, outside the scope of this paper and thus remain for future studies.

Concluding remarks

In each of the studied areas, one or more large-scale climatic oscillations affected snowfall-related climate parameters. The majority of the phenomena covered in this study have interannual oscillations, and the predictability of these oscillations is high on the climate research agenda. The predictability of ENSO has already led to improved seasonal forecasts, especially in tropical regions. Cohen and Jones (2011) suggest a new index that may improve the predictability of AO-NAO, which could improve winter climate predictions in the Northern Hemisphere. If such improvements come to fruition, for this and for other oscillations, their combination with information on correlations between oscillations and snow-related parameters could provide important information for winter sport management and powder lovers.

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