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The challenges of commercial mountaineering on the highest Volcanic Seven Summit, the Ojos del Salado

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Abstract

Commercial mountaineering has gained widespread popularity in recent decades. Global mountaineering challenges – e.g., the Seven Summits challenge to climb the highest summit of each continent – amplify this process, and also raise the profile of individual destinations. The highest volcano on the Earth, the Ojos del Salado in the Dry Andes (Chile/Argentina) is featured in two of the major challenges (Seven Second Summits, Volcanic Seven Summits). Thus, it is a prime extreme outdoor tourism destination. The relative ease of access and the non-technical nature of the ascent have also contributed to the increasing volume of tourism. However, our observations about commercial mountaineering practices reveal surprisingly low success rates on the summit. Based on data from our decade-long environmental monitoring programme and our field experiences,, we attribute this to the extreme environment and landscape of the mountain (e.g., cold and dry climate, strong winds, topographical situation, loose surface material), scarce mountaineering facilities, and potential misjudgements by inexperienced climbers.

Keywords: Ojos del Salado, Andes, outdoor tourism, commercial mountaineering, extreme environment, extreme landscape

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Introduction

The meaning of mountaineering has evolved significantly during the 20th century; from a form of elite activity – i.e. climbing a mountain with as little outside help as possible – to a wide-ranging term encompassing climbing, via-ferrata, backpacking, trekking and hiking in mountainous regions (Apollo, M. 2017). Due to the increasing popularity of outdoor sports and the growing availability of extreme travel destinations, the volume of amateur mountaineering has been increasing steadily during the last few decades. As the vast majority amateur mountaineers use commercial tour operators, high altitude mountain trekking and climbing represents a strongly emerging new form of tourism (Johnston, B.R. and Edwards, T. 1994; Apollo, M. 2017).

Widely known global mountaineering challenges have been playing a key role in the popularisation of professional and semi-professional mountaineering (Hamill, M. 2012; Romero, J. 2014; Buckingham, E. 2015).

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A classic example is the Seven Summits challenge to climb the highest summit of each continent *(Table 1*, column 2–3*)*, which was proposed in 1988 (Bass, M. *et al.* 1988; Bell, S. 2000). Newer mountaineering challenges are also emerging, e.g., the Seven Second Summits challenge to climb the second highest point of each continent (see *Table 1*, column 4–5) (Horrel, M. 2012), and the Volcanic Seven Summits to climb the highest volcanoes on all the continents (*Table 1*, column 6–7). The latter was proposed in 1999 and first completed in 2011 (Andalkar, A. 1999; Cairns, S. 2020; Traver, M. 2020; Rohnfelder, A. 2021; Stone, J. 2022).

Although several of these summits are technically, physically, and/or financially demanding to climb (e.g., Mount Everest, Vinson Massif), others are more accessible for amateurs and hiking enthusiasts (e.g., Aconcagua, Kilimanjaro, Puncak Jaya). Hence, while only a few hundred people have completed one of these challenges (Jurgalski, E. and Kikstra, H. 2016), the popularity of accessible and non-technical – i.e. no specialised mountaineering techniques and equipment required – summit challenge locations has skyrocketed due to the achievement and perceived prestige of climbing such a peak (Nüsser, M. and Dame, J. 2015). Although this brings economic benefits, there are growing concerns about the increased environmental strain on fragile high-mountain environments (Johnston, B.R. and Edwards, T. 1994; Marek, A. and Wieczorek, M. 2015).

The highest peak of the Volcanic Seven Summits – i.e. the highest volcano on the Earth – is the Ojos del Salado (6,893 m a.s.l.) in the Dry Andes on the border of Chile and Argentina. This peak, first climbed in 1937 (Carter, H.A. 1957), is also included in the Second Seven Summits challenge, which makes it a prime target for amateur mountaineers and outdoor enthusiasts. The Ojos del Salado boasts easy access on the Chilean side (used by > 90% of the climbers), moderate altitude compared to an 8,000 m high peak (while still being the highest peak in its category), no significant ice coverage (Nagy, B. *et al.* 2019), no volcanic activity, and no significant danger from falling due to exposed rock faces. Most of the ascent is achieved by trekking up on a footpath criss-crossing a steep scree slope, while only the last 30–40 m involves exposed climbing through a steep couloir and a ridge. However, holds and supports are abundant, and fixed ropes are also available to assist this last part of the ascent. These characteristics usually indicate a relatively easy ascent that is achievable for a wide-variety of prospective climbers, e.g., people without significant mountaineering and outdoor experience (Doran, A. and Pomfret, G. 2019). Due to these factors, the Ojos del Salado gained considerable fame and popularity in recent decades and attracts an increasing number of climbers.

However, the extreme environment of the mountain (e.g., it is one of the driest region of the Earth) is challenging for a lot of climb-

Table 1. Summits included in the different „Seven challenges"

Continent	Seven Summits		Seven Second Summits		Volcanic Seven Summits	
	Name	Height, m	Name	Height, m	Name	Height, m
Asia	Mount Everest	8,848	K2	8,611	Damavand	5,671
South America	Aconcagua	6,962	Ojos del Salado	6,893	Ojos del Salado	6,893
North America	Denali	6,194	Mount Logan	5,959	Pico de Orizaba	5,636
Africa	Kilimanjaro	5,895	Mount Kenya	5,199	Kilimanjaro	5,895
Europe	Elbrus	5,642	Dykh-Tau	5,205	Elbrus	5,642
*Europe**	*Mont Blanc*	*4,810*	*Monte Rosa*	*4,634*	*Etna*	*3,357*
Antarctica	Vinson Massif	4,892	Mount Tyree	4,852	Mount Sidley	4,282
Australasia	Puncak Jaya	4,884	Puncak Mandala	4,760	Mount Giluwe	4,367

*The highest summits for Europe vary among different listings, depending on how the boundary between Europe and Asia is defined.

ers – many of whom are unexperienced – and contributes to a very low success rate (below ~ 30%) of reaching the summit. This causes concerns about the sustainability of the business model of private tour operators, and also about the health and safety of climbers, especially if tourist numbers increase any further. Increasing tourism also leads to significant environmental degradation, especially in highly vulnerable extreme environments. Thus, the Ojos del Salado is a prime location to investigate the relationship between mountaineering tourism and the vulnerable environment of high-altitude mountains. Furthermore, conclusions learned on the Ojos del Salado are directly transferable to other high-altitude desert volcanoes in the Dry Andes (e.g., Llullaillaco, Socompa, Bonete, Pissis, Cerro Incahuasi) that are expected to see an increased number of visitors in the near future.

In this paper, we build on our decade long field experience on the Ojos del Salado (between 2008 and 2022) and the results of our environmental monitoring programme (Nagy, B. *et al.* 2019) to explore the effects of the extreme environment on commercial mountaineering activities and vice versa. We place a special emphasis on the environmental conditions/hazards that hinder successful summit ascents, the potential for environmental degradation due to mountaineering tourism, and provide suggestions about good mountaineering practices on the Ojos del Salado. We propose that these issues are relevant to a wide range of stakeholders, including academics (both in the natural and social sciences), policymakers, tour operators and climbers.

Geographical background

The Dry Andes is about a 1,000 km long section of the Andes, mostly located within Chile, Argentina, and Bolivia. The Ojos del Salado is the highest of several – mostly volcanic – peaks that rise above 6,000 m a.s.l. from the Puna de Atacama, i.e. a vast, high altitude (~ 4,000 m a.s.l.), and mostly uninhabited plateau in the Dry Andes *(Figure 1).*

The climate of these peaks and their vicinity is extremely harsh as they fall within the hyper-arid Andean Arid Diagonal, where precipitation – even at the highest altitudes – remains below 100 mm/year due to orographic and oceanic blocking (Amman, C. *et al.* 2001; Houston, J. and Hartley, A.J. 2003). Furthermore, the spatiotemporal distribution of the precipitation is highly sporadic and any snowpack sublimates in a matter of weeks – at the most – in the dry and windy environment (Vuille, M. and Ammann, C. 1997; Vuille, M. 1999). Hence, the climatic snowline is at an extremely high altitude of ~ 7,000 m a.s.l. – the highest on Earth – just above the tallest summits (Clapperton, C.M. 1994; Kull, C. *et al.* 2002; Grosjean, M. *et al.* 2007), which prevents the formation of glaciers and perennial ice coverage. However, some ice can be found underground in the permafrost (i.e. ground with temperatures below 0 °C for at least two continuous years) above 5,000–5,500 m a.s.l. (Gruber, S. 2012; Gjorup, D.F. *et al.* 2019; Nagy, B. *et al.* 2019, 2020). During summer months, the melting permafrost feeds a few small transient ponds above 6,000 m a.s.l. on the Ojos del Salado (Aszalós, J.M. *et al.* 2020a, b). Due to these extreme conditions, the region has been used as a Mars analog site by several studies (e.g., de Silva, S.L. *et al.* 2010, 2013; Favaro, E.A. *et al.* 2020; Kereszturi, Á. *et al.* 2020, 2022).

Historical overview of mountaineering on the Ojos del Salado

Based on historical information, and our own experiences since 2008, we delineate 4 stages (periods) of mountaineering and mountaineering tourism on the Ojos del Salado:

Period I. After the first expeditions in the mid-20th century, the 1980s and 1990s were characterised by low volume occasional uncommercialised mountaineering endeavours. In April, 1984 a helicopter of the Anglo-American Mining Co. of South Africa crashed on the mountain during a mining survey. As part of the salvage operations, bulldozers

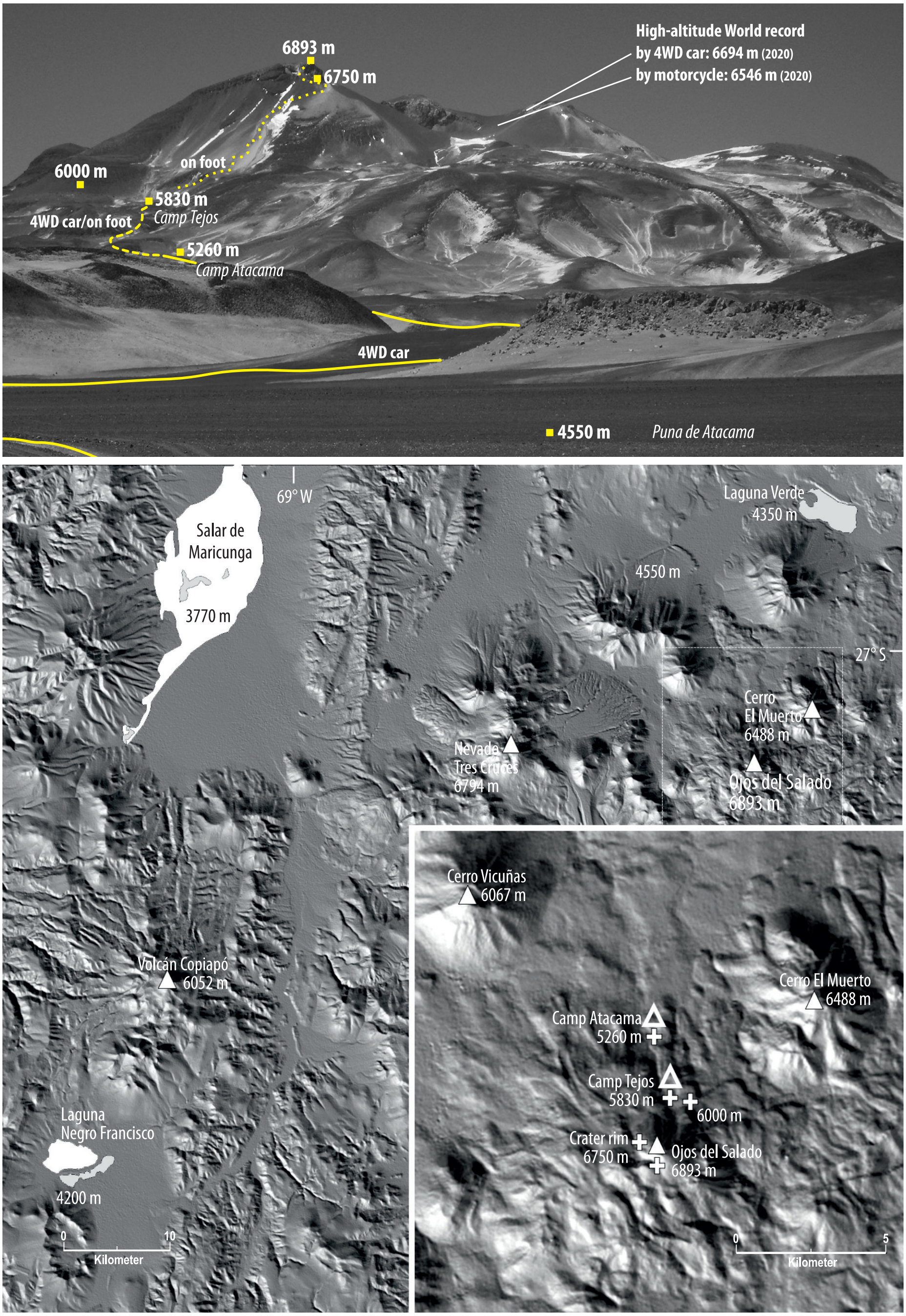

Fig 1. The Ojos del Salado, viewed from the Puna de Atacama plateau (February, 2016). Our climate monitoring sites, the normal mountaineering route, and the locations of several vehicular world records are indicated. The map inset shows the main camps (triangle) and the sites of included in our environmental monitoring program (cross). The nearest human settlement is ~ 150 kms away.

were used to create a dirt road – reaching 5,900 m a.s.l. – which was used to transport heavy equipment and a double container (Refugio Tejos/Tejos Camp at 5,830 m a.s.l.) serving as a base of operations *(Photo 1).* This access route is still in use today.

Period II. In 2004, the Aventurismo tour operator company got concession from the Chilean government for the Chilean side of the Ojos del Salado. The company was responsible for the development and maintenance of three camp sites located along the approach to the Ojos del Salado: Camp Laguna Verde (4,350 m a.s.l.), Camp Atacama (5,260 m a.s.l.), Camp Tejos (5,830 m a.s.l.) (see *Photo 1*). They provided communal dome tents, field radios, waste collection, and a mountain rescue service equipped with portable hyperbaric bags and oxygen canisters. These safety and comfort facilities contributed to the increasing volume of tourism on the Ojos del Salado, which was designated as a zone of special environmental/touristic interest (ZOIT: Zonas de Interés Turístico) in 2006 (Servicio Nacional de Turismo, 2006). The annual number of climbers were around 300–500 during this period.

Period III. After the Aventurismo concession ended in 2015, all the aforementioned

Photo 1. Mountaineering camps on the Chilean side of the Ojos del Salado. a = Tejos Camp at 5,830 m a.s.l. in February, 2020; b = Atacama Camp at 5,260 m a.s.l. in March, 2018; c = Laguna Verde Base Camp at 4,350 m a.s.l. in January, 2010, dome tents provided by Aventurismo during the concession period (between 2004 and 2015) are visible.

services and facilities on the mountain were discontinued. Hence, since 2015 the Ojos del Salado is an independent mountaineering destination, i.e. it is possible to access and climb the summit independently and without any compulsory fees. However, the lack of infrastructure also hinders independent commercial operators. During this period, which lasted about 3–4 years, visitor numbers stagnated at about 400–500 person per year.

Period IV. In 2018, paving the National Highway 31 between Chile and Argentina was completed. This road provides direct and quick access to the Laguna Verde Camp. Meanwhile, most facilities on the mountain – except organised mountain rescue – were re-established by independent tour operators. The majority of tour groups started using 4WD vehicles to ferry equipment and supplies (and sometimes climbers) up the Tejos Camp at 5,830 m a.s.l. Tourism became highly concentrated in time, about 90 percent of the 500–600 annual visitors (pre-covid terminus) come in January and February. This is causing environmental strain – e.g., the quick degradation of the campsites – and raising the risk of accidents (Marek, A. and Wieczorek, M. 2015). Meanwhile, there is still no enhanced environmental protection from the government, e.g., the nearby Nevado Tres Cruces National Park (established in 1994) does not cover the area.

Methods

Within the framework of our climate- and environmental monitoring programme which started in 2008 (http://permachile.com), we have gathered a significant amount of quantitative data about the environmental conditions – such as temperature, aridity, wind – that can affect and potentially limit commercial mountaineering activities in the region. Our data collection strategy focuses on the monitoring of permafrost and ground ice in every major environmental zone of the region. Thus, measuring ground temperature and humidity, using data loggers (HOBO Pro v2; operation range: −40 °C to 70 °C, accuracy: ±0.21 °C), is our key activity on the field (Nagy, B. *et al.* 2019). Our loggers are buried at different depths (10–60 cm) and at several locations between the elevations of 4,550 and 6,893 m a.s.l. (see *Figure 1*). The same data loggers are also used to record air temperature and humidity at two locations, near the Tejos Camp (though at the slightly higher elevation of 6,000 m a.s.l.), and on the Ojos del Salado summit (see *Figure 1*). To investigate wind speed and its capacity to transport sediment, we installed sediment-traps at 5,200 m and 6,000 m a.s.l. – near the Atacama and Tejos Camps respectively (see *Figure 1*). We also installed and operated a mobile meteorological station while staying at the Tejos Camp between 11–14, February, 2016, to measure radiation and energy balance, wind speed and direction, air temperature, air humidity, and dew formation. Besides, in-situ measurements and sampling, we also utilise satellite imagery – Landsat 7 ETM+, Landsat 8 OLI, and MODIS (Moderate Resolution Spectro-radiometer) – to survey the sporadic snow coverage (Nagy, B. *et al.* 2019).

Since 2008, our team – collectively – spent 10 summer climbing seasons (in 2008, 2010, 2012, 2014, 2016, 2018, 2019, 2020, 2022, 2023) on the Ojos del Salado, reaching the summit 9 times. A key difference between our presence and the activities of commercial tours is that we spend around 4 weeks – of which about 2 weeks is in the highest regions (i.e. above 5,800 m a.s.l.) – on the mountain continuously, whereas commercial tours typically spend about 1 week on the Ojos del Salado. This has provided us ample opportunity to interact with several commercial tours per climbing season and observe their activities. Hence, besides our numerical data, we can also rely on our extensive field experience on the mountain to evaluate – within the context of our environmental data – the common practices and mountaineering strategies of commercial tour operators. We also use official records from the Chilean Border Agency (DIFROL: Dirección Nacional de Fronteras y Límites del Estado) and the Chilean Tourism

Agency (SERNATUR: Servicio Nacional de Turismo) to assess tourism volumes (Servicio Nacional de Turismo, 2014) and success rates. However, there are several shortcomings of these data sources: (1) no official permits are required to climb the Ojos del Salado, foreigners need to obtain DIFROL permits but these are not related to climbing; (2) Aventurismo and other private operators do not maintain reliable public records about successful and unsuccessful attempts on the summit due to conflict of interest.

Challenging environmental conditions on the Ojos del Salado

As environmental conditions are substantial in determining the success on high altitude summits, climbers are in need of detailed information about the typical conditions on a mountain (e.g., snow coverage, water resources, typical temperature range etc.) and short-term predications (e.g., meteorological forecasts). Below we list and describe the most important and challenging environmental factors on the Ojos del Salado based on data obtained by our environmental monitoring programme. We also evaluate how these conditions affect the typical mountaineering strategies and activities of commercial tours – that we observed during our decade long presence on the mountain – with a special emphasis on providing best practice guidance.

Topographical situation and high altitude

Low oxygenation which might lead to acute mountain sickness (AMS), is the principal consequence of high altitudes on human physiology. This is caused by lower oxygen concentration at high altitudes due to lower air pressure. Respiratory humidification – i.e. attaining saturation water pressure in the airways and lungs – also has a proportionally greater effect in oxygenation at high altitude (Brown, J. and Grocott, M. 2013). In order to manage the problem of low oxygenation and to avoid AMS, a well-planned acclimatisation strategy is essential. However, preparing and executing this strategy is a major challenge on the Ojos del Salado due to the topographical situation of the summit and the wider region.

Successful acclimatisation requires a "climb high, sleep low" approach. However, the possibility of gradual ascent – i.e. no large jumps in sleep height but a large enough differences between sleep and climb heights – is limited on the Ojos del Salado as it towers ~ 2,500 m above the surrounding Puna de Atacama, a vast rocky desert plateau at around 4,000 m a.s.l. (see *Figure 1*). It is quite typical to start acclimatization ascends from the Puna de Atacama, thus, mountaineers spend most of their time (> 90%) above 4,000 m a.s.l. while climbing the Ojos del Salado. The medevac of AMS patients is also hindered by the large distances (> 100 km) on the high-altitude (> 4,000 m a.s.l.) plateau, though newly paved roads largely alleviate this problem. Settlements where medical help is available are even further, around 250 km from the mountain. These factors are compounded by the lack of organised mountain rescue services, which means that oxygen bottles and portable hyperbaric bags (Gamov bags) are not readily available on the mountain, and medevac needs to be organised ad hoc. The possibility of a vehicular ascent to 5,900 m a.s.l. is also tempting – especially for inexperienced tourists – and could lead to quick onset AMS cases.

Cold temperatures

As the Tejos Camp (5,830 m a.s.l.) is the main staging area for summit attempts, it is important to know typical temperatures in the vicinity of this site. The annual mean air temperature is -10.03 °C at 6,000 m a.s.l., based on our measurements between 2014 and 2020. Although a linear trend fitted on monthly mean temperatures between March, 2014, and March, 2020, reveals a warming of +2.42 °C *(Figure 2)*, summer climbing season

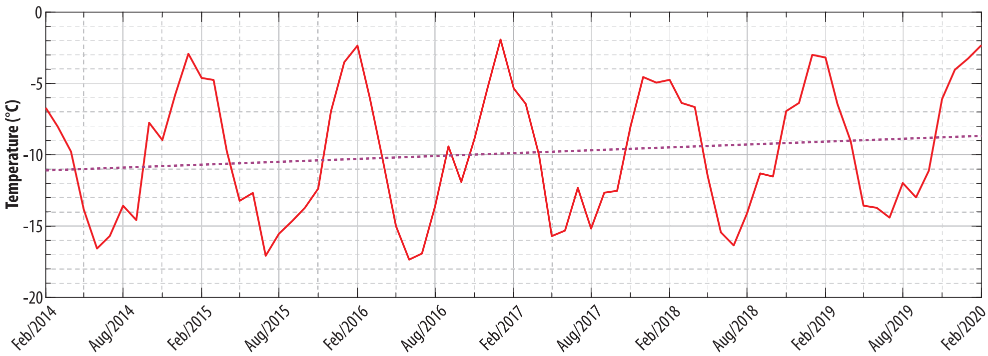

Fig. 2. Monthly mean temperatures at 6,000 m a.s.l. near the Tejos Camp between 2014 and 2020. A linear trend, showing the general warming, is also plotted.

(Dec-March inclusive) temperatures remained largely unchanged. Hence, we propose that the -6.22 °C mean climbing season (Dec-March) temperature is fairly representative for the Tejos Camp (see *Figure 2*). As summiting and returning takes about 10–15 hours from the Tejos Camp (5,830 m a.s.l.), starting before dawn, it is important to know the typical daily variability of temperatures.

Although the highest daily maximum temperatures (~ 19 °C) were observed in December, the overall daily temperature variability is more suitable for climbing in January (*Figure 3*). This is due to warmer minimum and average temperatures which are especially pronounced during the crucial early hours before dawn. On a typical January day, these early morning temperatures hold between -5 °C and -7 °C, while in December they consistently hover around -10 °C (see *Figure 3*). February is similarly suitable though slightly colder (by around 1 °C), while March is distinctively more cold in all regards, and, thus, less suitable for climbing. In fact, typical afternoon temperatures in March dip well below December temperatures (see *Figure 3*).

Our measurement site at 6,750 m a.s.l. is situated immediately above a steep 700 m high scree slope – the bulk of the elevation gain during climbing. This site is usually reached by climbers before noon. From here, climbers only need to ascend a further 150 m to the summit, though this ascent is on a steep rock wall – the most technically challenging part of the climb. This impressive and intimidating cliff is visible from this site, and many climbers give up at this point due to exhaustion and self-doubt (Nüsser, M. and Dame, J. 2015). The exposed and windy conditions at this location also contribute to the deterrence, thus, it is important to know the typical conditions here. Although our loggers are buried at 10 cm depth, we argue that they represent air temperatures well as the regolith is extremely coarse, porous, dry, and well ventilated (Nagy, B. *et al.* 2019). The annual mean (ground) temperature at this location during the 2012–2020 period is -14.86 °C. During midday, when most climbers reach the site, temperatures are at around -10 °C (see *Figure 3*). Similar to the Tejos Camp, January and February are the most favourable months for climbing, due to the mildest typical minimum temperatures (see *Figure 3*).

The last 30–40 m climb to the Ojos del Salado summit leads through a steep couloir, an exposed windy ridge, and crumbly bedrock. As the progress of climbers is slow and queueing might occur, especially with larger groups, timing the arrival well is crucial. Temperatures are generally favourable for

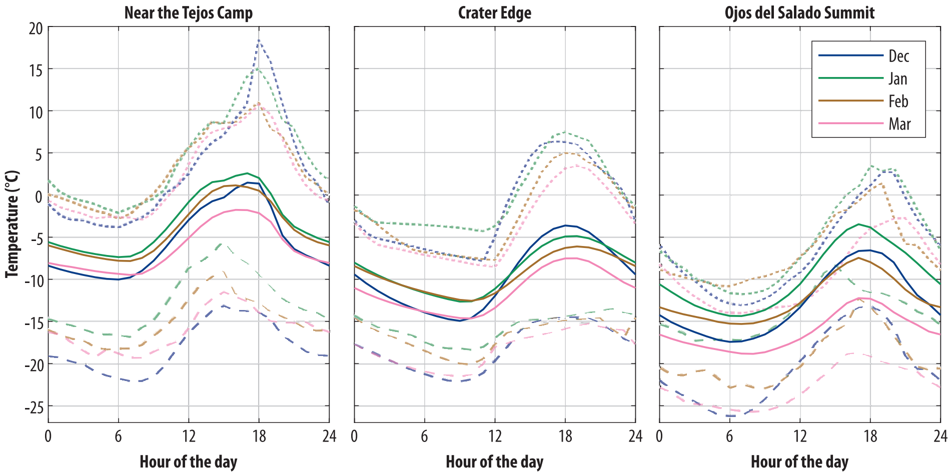

Fig. 3. The mean (solid line), minimum (transparent dashed line), and maximum (transparent dotted line) hourly temperatures measured between 2014 and 2020 near the Tejos Camp 6,000 m a.s.l (left); between 2012 and 2020 at the Crater Edge 6,750 m a.s.l. (middle); and between 2014 and 2015 at Ojos del Salado summit 6,893 m a.s.l. (right). Months of the climbing season (Dec, Jan, Feb, Mar) are calculated and plotted separately using different colours (see legend).

an early afternoon summitting (see *Figure 3*), which also avoids descending in harsh conditions. Similar to lower sites, January provides the best overall conditions, with minimum and mean temperatures between -10 °C and -5 °C (see *Figure 3*). However, these temperatures drop quickly on either side of January, with early afternoon minimums between -20 °C and -15 °C in December and February. Temperatures are even more harsh during the late climbing season in March, when early afternoon minimum temperatures are between -20 °C and -25 °C (see *Figure 3).*

Strong winds and wind chill

Although, long-term wind speed measurements are not available from Ojos del Salado, Milana, J.P. (2009) presented limited data from the Valedero Gold Mine (2000–2002), a comparable site on the Argentinian Puna de Atacama, though ~ 250 km to the south and ~ 3,000 m lower. These measurements indicate that wind-speeds between 50–100 km/h occur frequently, while wind-gusts between 250–440 km/h are also possible (Milana, J.P. 2009). As the climate is extremely arid, strong winds move and redistribute sediments easily. Hence, aeolian (wind formed) landforms such as sand dunes, ripple-marks, mega-ripples (Milana, J.P. 2009; Nagy, B. *et al.* 2019), and bedrock wind abrasion *(Photo 2)* are abundant in the region. Our sediment traps at 6,000 m a.s.l. also confirm strong wind action, as grains larger than 5 mm – significantly coarser than the sand fraction (0.05–2.00 mm) – were found in the sediment trap 50 cm above the surface. Strong wind can endanger climbers at the exposed final approach, thus, it is recommended to monitor wind levels continuously during summit ascents. The presence of coarse windblown debris – with grain sizes that can surpass that of the sand fraction – is also a key problem (see *Photo 2*). For example, it can lead to injuries of the cornea, thus, using protective glacier/ski googles is highly recommended. Abundant wind-blown sediment also significantly deteriorates the camping experience (e.g., sand filling tents and sleeping bags, and contaminating meals), which contributes to the exhaustion of climbers.

Photo 2. Aeolian processes on the slopes of the Ojos del Salado. a-b = Megaripples near the Atacama Camp at 5,250–5,300 m a.s.l. (February, 2020); c-d = wind-abrasion of a boulder (c: windward side, d: leeward side) at 5,900 m a.s.l. (February, 2012); e/1-2 = sandstorm on the lower slope of the Ojos del Salado at 5,300 m a.s.l. (February, 2010).

However, the most important consequence of strong wind is its negative effect on apparent temperature, as moving air leads to more intensive/quick body heat loss, i.e. wind chill (Eq. 1).

$$T_{wc} = 13.12 + 0.6215 \cdot T - 11.37 \cdot v^{0.16} + 0.3965 \cdot T \cdot v^{0.16}, \quad \text{(Eq. 1)}$$

where T_{wc} is wind chill equivalent temperature (°C), T is air temperature (°C), and v is wind velocity (km/h).

Wind chill is especially problematic during summit attempts due to the combination of early morning low temperatures and high winds. Even a very mild 10–20 km/h wind – which is almost constant in the region – can lead to wind chill equivalent temperatures (apparent temperatures) of -10 °C and -15 °C at the Tejos Camp during a typical January morning (*Figure 4).* This can easily become 5–10 °C colder on either side of January or simply due to stronger winds. Wind chill might also negate warming which occurs later in the afternoon (see *Figure 4*), as winds generally pick up speed in parallel with the warming. It is notable, that even though temperatures appear suitable late in the climbing season (e.g., March) wind chill might cause apparent temperatures around -30 °C on the summit (see *Figure 4*) making frostbite of the extremities a distinct possibility. This illustrates the problems with winter climbing, when daily mean temperatures on the summit are at around -25 °C while apparent temperatures can dip below -40 °C.

Low precipitation and humidity

There are no in-situ precipitation measurements from the highest regions of the Puna de Atacama, but numerical estimations yield very

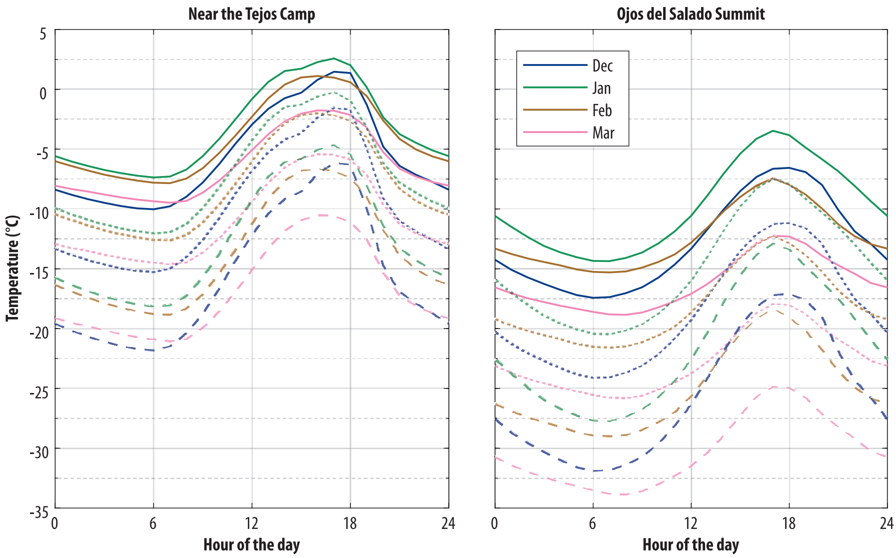

Fig. 4. Typical daily temperatures during the climbing season – i.e. mean of the hourly temperatures – and the corresponding wind chill equivalent temperatures at 10 km/h (transparent dotted line) and 50 km/h (transparent dashed line) wind speeds near the Tejos Camp 6,000 m a.s.l. (between 2014 and 2020) (left); and at the Ojos del Salado summit 6,893 m a.s.l. (between 2014 and 2015) (right).

low values that are consistent with a desert environment even at high elevations (Amman, C. *et al.* 2001). Thus, this area can be considered the highest desert on Earth, where precipitation and snow coverage is extremely sporadic and low. However, strong individual precipitation events can occur due to special synoptic metrological circumstances (Wilcox, C.A. *et al.* 2016), e.g., April, 2015 and February, 2018 *(Figure 5).* Sudden, local snow storms can also occur almost any time, though they rarely cover the whole mountain. These snow storms mostly arrive from the east and they can be electrically charged, e.g., our loggers on the summit were burned by a lightning storm in 2013.

The low precipitation and strong sublimation – due to the dry air, high wind, and strong insolation – strongly limit the persistence of snow on the ground. Thus, during the summer climbing season, the mountain is mostly snow free at around 5,000 m a.s.l., and even at around 6,000 m a.s.l. snow usually only persists for a few weeks (see *Figure 5*). This scarcity of reliable local freshwater supply force climbers to transport their whole stock of drinking water from Copiapó, 250 km away. Despite the lack of a spatially and temporally consistent snowpack on the mountain, local sheltered snow patches occur, especially near the crater rim where they are present in most years (see *Figure 5*). If the snow cover/patch is fresh and thick, it represents a significant obstacle for climbers, though sublimation can quickly diminish this. Refrozen snow patches are fairly easy to traverse by crampons, though it is important to do this well before midday before any significant melting. The aforementioned sudden precipitation events (synoptic or local) can also unexpectedly disrupt the climbing process, as most climbers only plan to spend a few days at the Tejos Camp. Furthermore, climbers are usually unprepared to deal with snowy/icy conditions in this extremely arid environment. Thus, a large proportion of climbers turn back from around 6,300–6,500 m a.s.l. in snowy conditions.

Low precipitation, the scarcity of sur face snow, ice, liquid water, and strong winds all

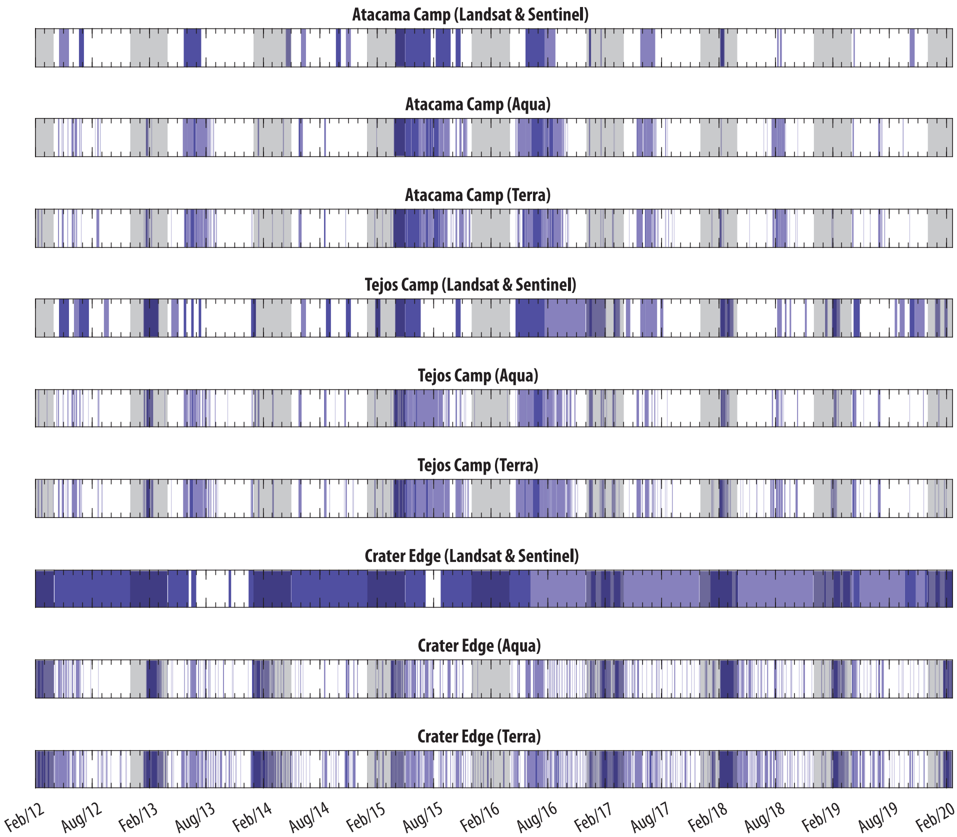

Fig. 5. Snow cover (light blue: partial snow coverage; dark blue: full snow coverage) at the Atacama Camp (5,260 m a.s.l.), Tejos Camp (5,830 m a.s.l.), and Crater Edge (6,750 m a.s.l.). Data is derived from Landsat and MODIS (aboard both Aqua, and Terra satellites) imagery for 2012–2020. Grey highlights represent the climbing seasons.

contribute to the extremely low water vapor content of the air (i.e. humidity). According to our measurements, the absolute (i.e. volumetric) air humidity (AH) – mass of water vapor divided by the volume of the air and water vapor mixture – near the Tejos Camp (at 6,000 m a.s.l.) is ranging between 0.5 and 1.5 g/m^3 during a typical climbing season morning *(Figure 6).* This is only about 5–15 percent of the optimal range of 9–13 g/m^3, i.e. 40–60 percent relative humidity at room temperature (Sterling, E.M. *et al.* 1985; Vellei, M. *et al.* 2017). Extremely dry air is even more pronounced on the Ojos del Salado summit, where the typical daily maximum AH is only about 1 g/m^3, ~ 8–11 percent of the normal range. Early afternoon – the typical time of summitting – AH is even lower at around 0.5 g/m^3, ~ 4–6 percent of the normal range (see *Figure 6).* Extremely low humidity is a major health concern for climbers (Davies, E.D. *et al.* 2016; Ladd, E. *et al.* 2016) as – compounded by the high rate of respiration – it leads to the severe drying of the skin around the mouth and nose and the mucosal lining of the airways (Tsutsumi, H. *et al.* 2007; Takada, S. and Matsushita, T. 2013). The dry

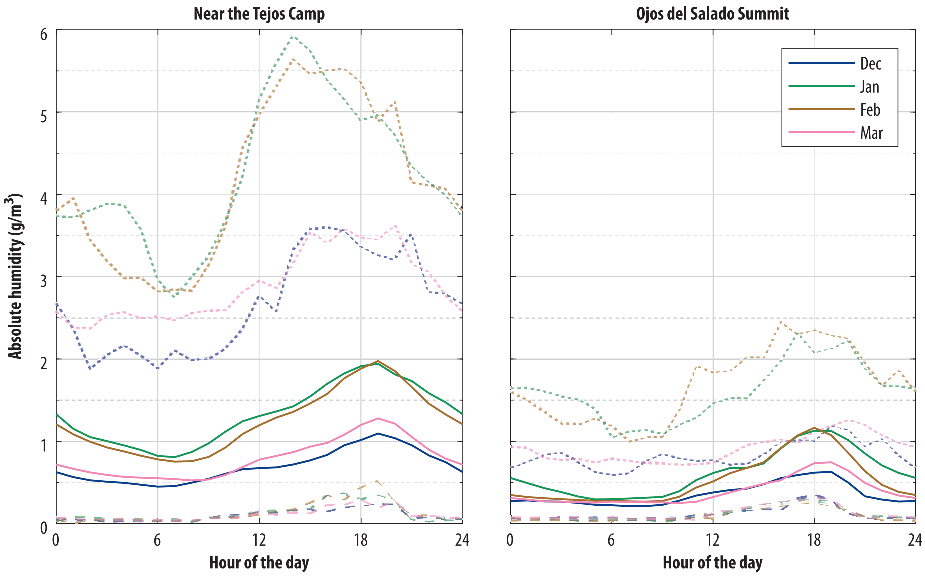

Fig. 6. The mean (solid line), minimum (transparent dashed line), and maximum (transparent dotted line) of the hourly absolute air humidity (g/m^3) measured between 2014 and 2020 near the Tejos Camp 6,000 m a.s.l (left); and between 2014 and 2015 at Ojos del Salado summit 6,893 m a.s.l. (right). Months of the climbing season (Dec, Jan, Feb, Mar) are calculated and plotted separately using different colours (see legend).

mucosa of the larynx could produce a dry, hacking cough named high altitude bronchitis (Cogo, A. *et al.* 2004; Ladd, E. *et al.* 2016), and skin dryness could also lead to injuries of the epidermis.

High insolation

The sky is usually clear until early afternoon in the climbing season, with mild overcast conditions typically prevailing later in the day. Although our records are short – just 3 complete days in February, 2016 – they indicate extremely high solar irradiation with hourly averages at around 1,100 W/m^2, even during overcast conditions *(Figure 7).* We propose that this is due to the combination of high altitude and extremely low humidity which cause very low scattering of the incoming solar radiation (global radiation). Individual instances of higher insolation than 1,370 W/m^2 – i.e. solar irradiation at the top of the atmosphere – were also measured occasionally. We propose this is caused by reflection from high level clouds (Breuer, H. *et al.* 2020).

Dry, crumbly and unstable debris cover

Most of the Ojos del Salado mountain is covered by an unsorted (i.e. containing various grain sizes mixed together) mantle of debris/regolith, predominantly containing sand, pumice, and pyroclastic debris *(Photo 3)*. Although permafrost is present above 5,600–5,800 m a.s.l. on the Ojos del Salado, ice that could cement the regolith is almost completely absent from the upper layers of the debris mantle during the summer climbing season (Nagy, B. *et al.* 2019). This is due to the low overall water content of the regolith – caused by the combination of arid climate and high porosity – and the presence of a 20–70 cm active layer (i.e. zone with temperatures above 0 °C underlain by permafrost) during the summer (Nagy, B.

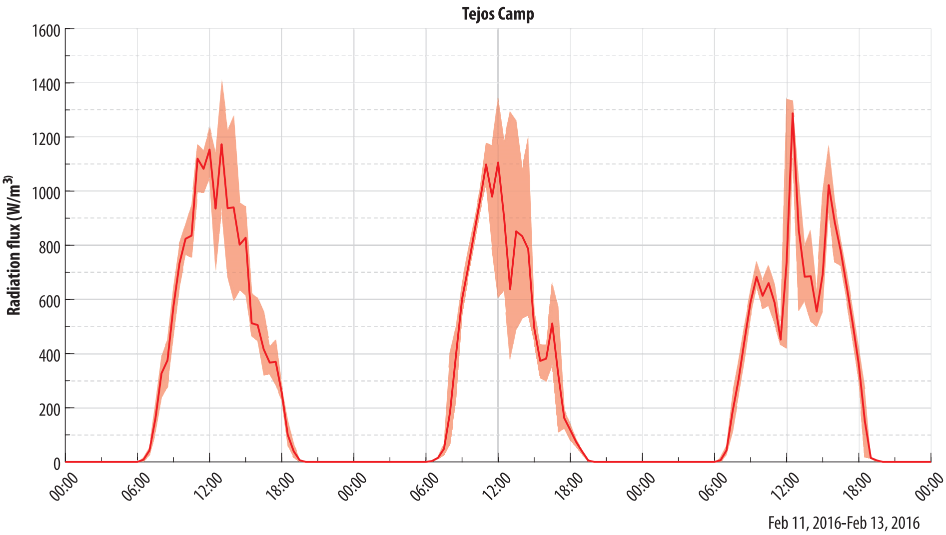

Fig. 7. Incoming solar radiation at the Tejos Camp (5,830 m a.s.l.) during 3 days in February, 2016. The solid line represents the average incoming radiation, while the shaded area represents the minimum-maximum range for each 30 minute measurement period.

Photo 3. High mountain desert-surface of the Ojos del Salado, a = coarse lag gravel pavement at 5,650 m a.s.l. (February, 2010); b = eolian sand-blanket at 5,840 m a.s.l. (February, 2016); c = sandy debris slope near the Camp Atacama at 5,350 m a.s.l. (January, 2012).

et al. 2019, 2020). Hence, the surface is extremely loose/unconsolidated which makes walking/climbing difficult and exhausting due to repeated slipping.

The unconsolidated surface material also intensifies the strong aeolian action in the vicinity of the Ojos del Salado (see section *Strong winds and wind chill*). This leads to the formation of thick sand layers or small sand dunes at around 5,000–5,800 m a.s.l., which are difficult to traverse (see *Photo 3*). The removal and redistribution of finer sediments can also leave behind coarse grained lag gravel pavements. Although these areas appear stable, usually the underlying fine sediments cannot support the weight of an adult, thus, walking across these is challenging as well (see *Photo 3*, a).

A summary of key challenges during different climbing stages

Conquering the Ojos del Salado is a fairly monotonous experience for most, as climbers usually spend more than a week in the close vicinity, which is a barren rocky desert. This physically and mentally draining experience is exacerbated by the unique combination of harsh environmental conditions. The topographical situation of the Ojos del Salado also hinders the planning and execution of a successful acclimatisation strategy. The high altitude, strong irradiation, dry air, strong winds all contribute to the severe dehydration and strong coughing that afflicts most climbers. Furthermore, even though actual air temperatures are not particularly low in the climbing season, strong wind chill could lead to frostbites. Unstable and slow walking on to the highly porous, dry and crumbly debris cover is a continuous problem which contributes significantly to the exhaustion of climbers. This debris covers and the strong winds also make camping a challenging, uncomfortable which hinders the relaxation and recovery of climbers. In fact, several geographical names in the region indicate physical hardship, isolation, hopelessness (e.g., Cerro Mulas Muertas – Peak of the Dead Mules; Cerro El Muerto – Dead Peak, etc.) which might reflect the challenges early explorers faced.

The most physically and mentally challenging – though technically easy – part of climbing the Ojos del Salado is trekking up the exposed, steep scree slope between Tejos Camp and the crater rim (6,000 to 6,750 m a.s.l.). Although this section of the climb just requires following the zigzagging footpath up the slope, resting places are scarce and the surface debris is very unstable. Thus, climbers often slide one or two steps down which is exhausting and frustrating. A large proportion of the climbers give up the attempt on the summit in the middle of this slope, at around 6,300–6,400 m a.s.l. A fairly consistent snow/firn patch also intersects the footpath to the summit at around 6,500 m a.s.l. that usually poses a significant challenge for climbers. In most cases, crampons are needed here – especially during the early hours – which are challenging to equip on the steep scree slope.

At the top of the scree slope, on the crater edge, the largest challenge is mostly psychological.Climbers catch their first up-close glimpse of the Ojos del Salado summit from this location. The steep rocky peak about 150 m above the crater rim, looks intimidating for the inexperienced. This, combined with the exhaustion due to the long climb on the scree slope and the unpleasant cold and windy early morning weather nudges many to turn back. Also, the bright orange container at the Tejos Camp is well visible from here, which tempts many to retreat to its comparable comfort.

Scaling the actual peak from the crater rim, especially the last 30–40 m, is technically the most difficult part of the climb. However, turning back is not common at this point as the summit is very close. A special source of danger on the Ojos del Salado is the long and tiring descent down the scree slope, which usually happens late in the afternoon. Climbers are the most exhausted at this stage and usually have lower coordination of their movements. This, on the unstable surface can lead to injuries and many unscheduled resting stops, partly due to frustration. Exhausted climbers who might descent on their own could – and sometimes do – fall asleep during these rest stops, which is dangerous as temperatures drop quickly at sunset.

Conclusions

The Ojos del Salado became a popular high altitude mountaineering destination in recent years, though the success rate of summit attempts is low. Although mountaineering infrastructure is quite sparse in the region, vehicular approach is easy due to recent road upgrades. Thus, we propose that the most important factor that hinders climbers in reaching the summit – and causing low success rate – is the harsh environment of the region, and the lack of proper consideration of these conditions. High altitude, cold temperatures, and strong winds are common environmental conditions on all major peaks. However, on the Ojos del Salado, these are exacerbated by extreme aridity, monotone desert landscape, and unstable surface material, which strongly accentuate other environmental challenges associated with the high altitude.

Ensuring gradual acclimatisation on the Ojos del Salado is paramount. Although it is relatively easy to reach high altitudes – e.g., the Atacama Camp (5,260 m a.s.l.) or even the Tejos Camp (5,830 m a.s.l.) – by a 4WD car, climbers should start acclimatisation well before they reach the Atacama Camp, and should continue the process even after that point. However, since the mid-2000s demand for quick and easy access to the mountain has increased. Thus, in a lot of cases, mountaineering equipment and supplies (drinking water, rations, etc.) are transported by car to the Tejos Camp, and a few days later the climbers are also ferried up. Summit attempts start from there, and climbers usually descend back to the Atacama Camp. An even more extreme form of this, is using cars to get to the Tejos Camp during the night, summit during the day, and then return to lower altitudes (even as low as sea-level) as quickly as possible.

We propose that the best strategy to safely – but also "cleanly" – climb the Ojos del Salado, is utilising vehicular transport to a limited degree. In this case climbers should spend several nights on the Puna da Atacama, and complete acclimatisation hikes there. Then, they can be transported up to the Atacama Camp by cars, but they should not utilise cars to reach higher altitudes. Cars can also be used to transport supplies and a limited amount of equipment to the Atacama and Tejos Camps. However, using cars have several consequences, beyond tarnishing the achievement of reaching the summit. Chief among these is the environmental degradation, e.g., erosion and noise pollution, and also the larger amount of waste production due to easier transportation. Unfortunately, independent waste collection and removal is still not organised around on the Ojos del Salado.

Despite these concerns, further increase in tourism and significant investments in infrastructure are expected on the Ojos del Salado for several reasons: (1) it is a prime non-technical, extreme-environment, high-altitude peak which fits very well into the profile of the extreme outdoor tourism industry; (2) it is part of the popular Volcanic Seven Summits and Second Seven Summits mountaineering challenges; (3) vehicular access is easy and cheap due to the newly upgraded international highway in the vicinity, and the presence of bulldozed dirt roads that are accessible with 4WD cars.

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