

Rime Mushrooms on Mountains

Description, Formation, and Impacts on Mountaineering

BY C. DAVID WHITEMAN AND ROLANDO GARIBOTTI

Rime mushrooms, commonly called ice mushrooms, build up on the upwind side of mountain summits and ridges and on windward rock faces. These large, rounded or bulbous accretions of hard rime range from pronounced mounds to towering projections with overhanging sides (Figs. 1, 2, and 3).

They may appear seasonally or persist indefinitely, posing challenges to climbers.

Rime mushrooms form when clouds and strong winds engulf the terrain. Supercooled cloud droplets are blown onto subfreezing surfaces and freeze rap-

“It was now my lead block, starting the 4th pitch, the big rime-whale towered above me. I felt small and didn’t see any good solutions other than venturing out into the middle of it. Doing that would mean 100 meters of severely overhanging face climbing on rime-covered ice. I kept going up and my heart suddenly jumped—on the right side of the mushroom a bluish half pipe appeared winding its way upward. I have learned during my climbs in Patagonia that very often, where the strong wind forms mushrooms, it also grinds out half pipes and tunnels. Higher up, the half pipe shut down—of course it couldn’t be this “easy.” My heart sank a little; it totally closed, and above was a 3-meter, 45-degree roof of rime leading out into the blue sky. Then I remembered the option I had seen from below: I had seen a bluish glint on the very belly of the beast. I decided to traverse left and find the blue gold. We were not going down yet!”

—BJØRN-EIVIND ÅRTUN, *who, with Ole Lied, climbed a new route, Venas Azules, on the South Face of Torre Egger in the Cerro Fitz Roy massif of Patagonia in December 2011. (Abridged and edited from its original version.) Bjorn-Eivind died in a tragic climbing accident in Norway in February 2012.*



FIG. 1. Impressive rime mushrooms on the summit and west face of Cerro Torre, Argentina. The Ragni (Spider) route is indicated. It starts from the Col de la Esperanza (right) and ascends the bulky rime mushroom called El Elmo (the Helmet), then the west face through a series of rime mushrooms leading to the summit mushroom. The mushroom just below the summit is 50 m tall and hangs over the north, west, and south faces. The mushroom on the summit platform itself is 20 m tall and hangs over the north and east faces. (PHOTO: Rolando Garbotti)

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FIG. 2. Rime mushrooms in a range of sizes cover the summit of Torre Egger in the Cerro Torre Massif, Argentina. Climbers Ole Leid and Bjørn-Eivind Årtun have reached the summit after completing a new route named Venas Azules. (PHOTO: Jorge Ackermann)

idly, making an opaque “hard” rime with air trapped between granular deposits. The mushrooms are most frequent and best developed on isolated summits and exposed ridges in stormy coastal areas. In describing rime mushrooms, their formation, where they have been reported, and their impact on mountaineering, we will focus on Southern Patagonia. Climbers have documented very large, well-developed mushrooms there (see acknowledgments).

COMPOSITION. As rime mushrooms persist, they are exposed to snowfall, graupel, rain, and drizzle. Melt-freeze cycles and solar radiation can also affect the consistency of the ice. In addition, rime mushrooms may incorporate soft rime, clear rime, and even glaze. *Soft rime* forms when water vapor deposits onto a cold surface to produce ice without changing to liquid first. Soft rime is feathery and when deposited onto an existing snowpack is called surface hoar; on other objects it is often called hoar frost. Unlike hard rime, soft rime forms during clear skies and weak winds, and when near-surface air is supersaturated with respect to ice. It forms predominantly

at night. *Clear rime or ice*, contrary to its name, alternates opaque and clear layers. Supercooled cloud droplets freeze as granules on impacted surfaces to form opaque layers with less air than hard rime. In clear layers, cloud droplets spread as a thin layer of water that then freezes. Whereas the three types of rime are frozen cloud droplets, *glaze*, a smooth, compact, transparent layer of ice, forms when supercooled rain or drizzle droplets, which are much larger than cloud droplets, coalesce and spread across a surface and then freeze.

Rime mushrooms, like the snow in a snowpack, are thus heterogeneous and constantly in dynamic equilibrium, with energy and mass exchanges and water phase changes at the atmosphere-ice boundary and metamorphic changes within the rime formation.

METEOROLOGICAL CONDITIONS. The higher the total mass of supercooled cloud droplets in a unit cloud volume and the higher the wind speeds, the larger the rate of accumulation of rime.

The rate of increase of rime mass on an obstacle can be approximated by

$$dM/dt = \alpha wU A \text{ [kg s}^{-1}\text{]}, \quad (1)$$

where w is the supercooled liquid water content (kg m^{-3}) of the cloud, U is wind velocity (m s^{-1}), A is



FIG. 3. Rime mushrooms on Cerro Torre. (PHOTO: Rolando Garibotti)

the area of the obstacle perpendicular to the wind, and α is the droplet-obstacle collision efficiency (a number between 0 and 1).

The droplet-obstacle collision efficiency is less than 1 because the wind splits around the obstacle; some cloud droplets do not collide with the obstacle. The collision efficiencies on rime mushrooms are not known, but can be expected to vary across the surface of an obstacle. The mean liquid water content of stratus, stratocumulus, and cumulus clouds is generally between 0.15 to 0.9 g m^{-3} . If a 1-m^2 obstacle were perpendicular to a 10-m s^{-1} wind, with a collision efficiency of 0.1 , and the liquid water content were 0.3 g m^{-3} , then rime would build up at the rate of 26 kg per day.

While the mass of a rime accretion is the same as the mass of the supercooled water droplets hitting the obstacle, the density of rime is lower than that of liquid water because of the air spaces. The amount of air incorporated—and therefore the density—depends on wind speed, ambient temperature, droplet diameter, and liquid water content. The density of rime typically varies from that of solid ice, 900 kg m^{-3} , down to 100 kg m^{-3} . Using the example of a rime mass buildup of 26 kg per day, which would produce a water depth of 2.6 cm , and assuming the rime density were 600 kg m^{-3} , the 24-h rime buildup on the surface would be 4.3 cm deep. In this example, rime would accumulate rather rapidly.

Supercooled droplets are most likely in a cloud at subfreezing temperatures from about -2° to -10°C . At 0° to -2°C , the heat liberated when the droplets freeze can warm the impacted surface, resulting in water running off and forming clear rime rather than lower-density hard rime. Depending on wind speed and cloud liquid water content, this process can occur over a range of subfreezing temperatures, but it is most likely at temperatures near freezing. Below -10°C , the probability increases that cloud droplets

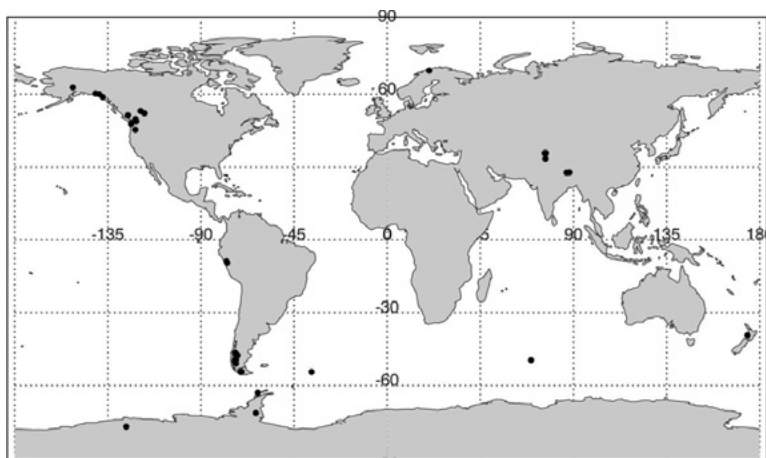


FIG. 4. Reported permanent or semipermanent rime mushrooms.

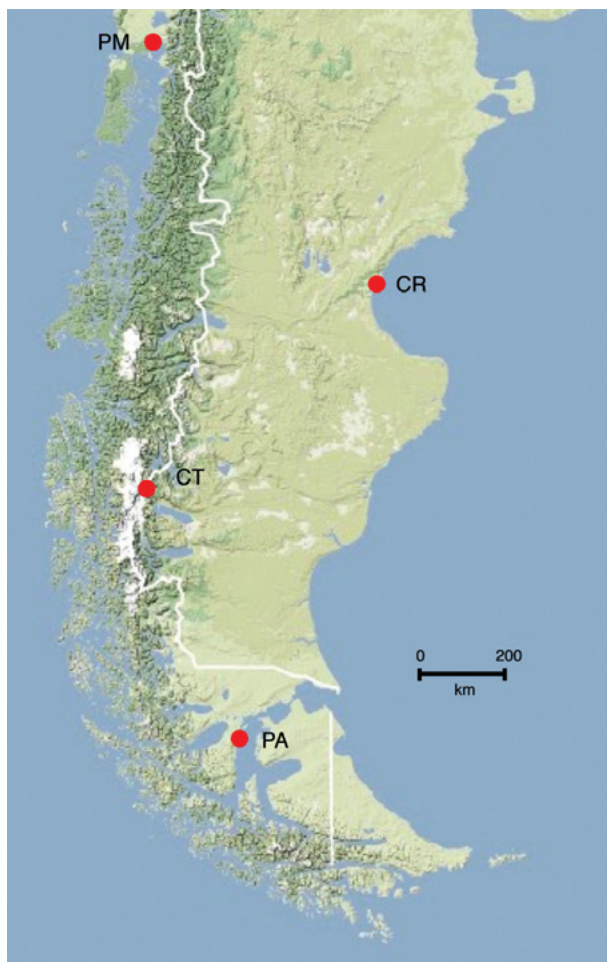


FIG. 5. The snowy northern Patagonian Ice Cap is 225 km north-northwest of Cerro Torre (CT) in the Cerro Fitz Roy Massif. The Southern Patagonian Ice Cap extends from northwest of CT southward. Soundings from the Puerto Montt (PM), Comodoro Rivadavia (CR), and Punta Arenas (PA) radiosonde stations are regular at 1200 UTC and occasional at 0000 UTC. Each station had more than 10,900 radiosonde ascents. Monthly means are determined by averaging the separately determined 0000 and 1200 UTC monthly means. [Background image from Google Maps.]

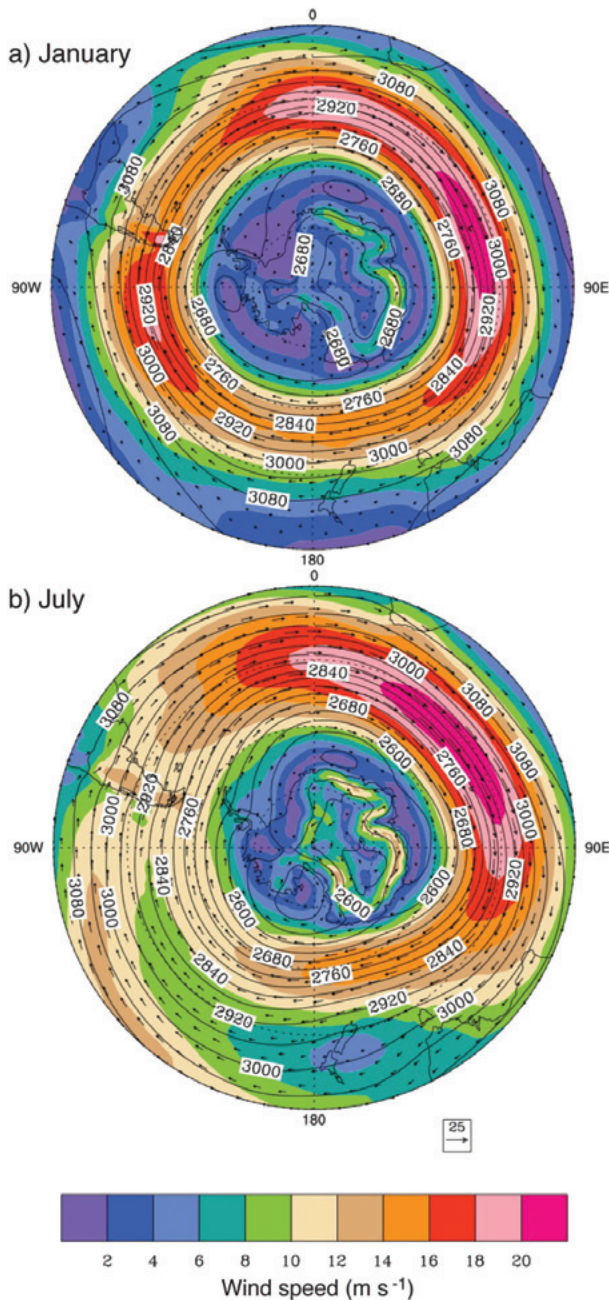


FIG. 6. Monthly mean ERA-Interim reanalysis of 70-kPa geopotential heights in MSL (solid lines with labels), wind vectors (25 m s⁻¹ west wind vector shown in legend), and isotachs (colors in legend) for the higher latitudes of the Southern Hemisphere in (a) January and (b) July. Patagonia is at about 70°W longitude.

will freeze rather than remain supercooled, because more ice nuclei become activated and the supercooled droplets are more likely to come into contact with frozen precipitation particles. The mass of supercooled

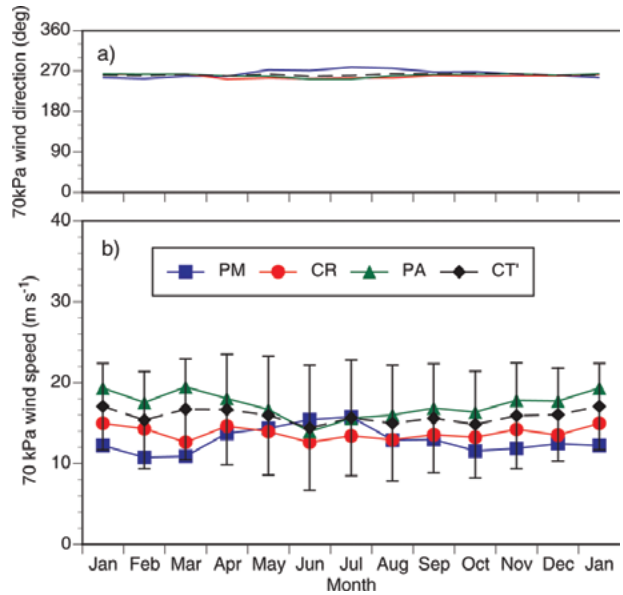


FIG. 7. Monthly 70-kPa (a) vector-average wind directions and (b) arithmetic-average wind speeds (m s⁻¹) at Puerto Montt, Comodoro Rivadavia, and Punta Arenas. In (a): estimated wind direction (dashed line) over the Pacific coast at the latitude of Cerro Torre (CT'). In (b): estimated wind speeds for the same location (dashed line) and the estimated standard deviations (vertical black lines). See Fig. 5 for site locations and abbreviations.

liquid water increases as air with temperatures below 0°C is forced upward by steep mountains.

TOPOGRAPHIC AND GEOGRAPHIC FACTORS. Topography affects the formation of rime mushrooms. Elevation is important because winds are commonly stronger at higher elevations, as are the subfreezing temperatures required for supercooled droplets. Towering, isolated peaks in particular often create *cap clouds* that expose upper slopes to supercooled droplets.

Mountains force approaching air masses to rise, resulting in cooling. This orographic lifting produces the cloud condensate necessary for rime accretion if the approaching air mass is moist enough and the lifting altitude is sufficient to form a cloud base below the summit. If sidewalls are steep, air close to the peak ascends rapidly, adding significantly to the cloud condensate by enlarging existing cloud droplets and initiating the formation of new droplets. The rapid ascent leaves little time for the droplets to freeze. The increase in the size and number of cloud droplets produced by orographic lifting, as well as the increase in wind speed with elevation, increase rime

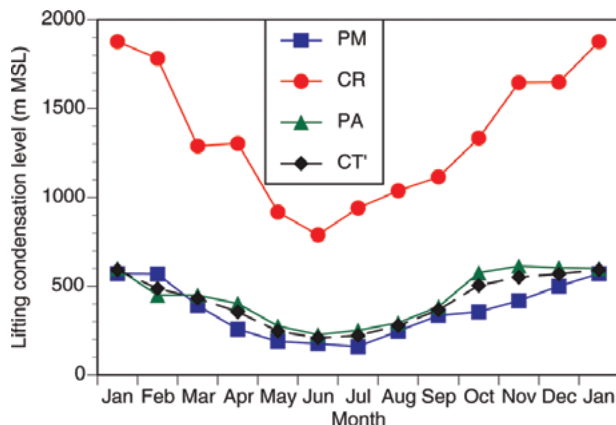


FIG. 8. Monthly mean LCLs at Comodoro Rivadavia, Punta Arenas, and Puerto Montt, and estimated LCL over the Pacific coast at the latitude of Cerro Torre (CT'). For reference, the elevation of Cerro Torre's summit is 3,128 m MSL. See Fig. 5 for site locations and abbreviations.

accretions with altitude on a mountain. On a smaller scale, the rime mushrooms are bulbous because the increase in wind speed with height near the ground increases rime accretion with height on an obstacle.

Topographic irregularities often channel air rising on the upwind side of a mountain. Wind speeds increase when air is channeled, enhancing rime mushroom formation where the ascending air goes through gullies and over ridges and summit plateau edges.

Location is also significant. Rime mushrooms are more likely where large-scale weather patterns produce low clouds and persistent high winds from a predominant direction. Downwind of a body of water that remains unfrozen year round and is large enough to supply significant moisture, summits favor persistent mushrooms if they are high enough above the water for lifted air to cool sufficiently.

WHERE RIME MUSHROOMS ARE FOUND.

Rime mushrooms are familiar primarily to mountain climbers, so we searched for them in the *American Alpine Journal* (1929 to present; www.americanalpineclub.org/p/aaj). We also used a Google Internet search and discussions with well-traveled climbers. The number of reports was small (about four dozen), and our resulting map (Fig. 4) may be biased because most communications were with climbers who have extensive experience in Patagonia.

The southern spine of the Andean Cordillera is well known for rime mushroom formation. Rime mushrooms have also been reported in the coastal

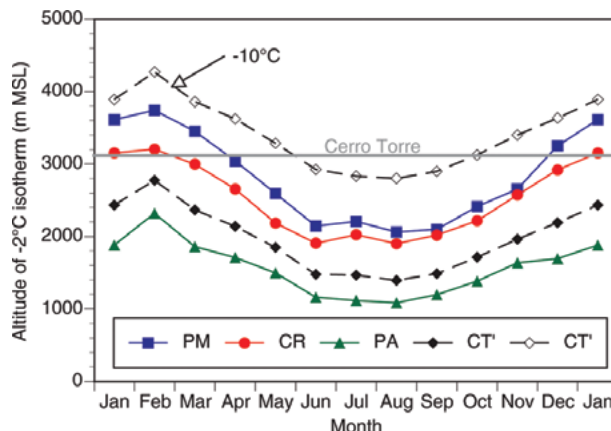


FIG. 9. Altitude of the -2°C isotherm as a function of month of year at Puerto Montt, Comodoro Rivadavia, and Punta Arenas, based on radiosonde data. Also shown are the estimated altitudes of the -2° and -10°C isotherms at the Pacific coast at the latitude of Cerro Torre (CT'), obtained by a latitudinal interpolation between Puerto Montt and Punta Arenas. The horizontal gray line indicates the altitude of Cerro Torre's summit. See Fig. 5 for site locations and abbreviations.

ranges of North and South America, on the Antarctic Peninsula, on the South Shetland and South Georgia islands of the Southern Ocean, in northern Scandinavia, and in portions of the Himalayas impacted by the Asian summer monsoon. The highest summits in the Himalayas have a more continental climate and are more likely to build up snow cornices downwind of obstacles rather than rime mushrooms on the upwind side. Many locations where heavy accumulations of seasonal rime are reported do not experience large or persistent rime mushrooms, which cannot be sustained through the summer in temperate climates.

CONDITIONS IN SOUTHERN PATAGONIA.

Patagonia is a geographic (rather than political) name for a large region in southern Argentina and Chile. Southern Patagonia includes two well-known Andean landscapes: the Cerro Fitz Roy massif in Argentina and the Torres del Paine massif in Chile. These high mountains are separated from the Pacific Ocean by the Southern Ice Cap, the largest ice field in the Southern Hemisphere outside of Antarctica, with an area of about 16,800 km² (Fig. 5) and a mean elevation of about 1,500 m MSL. The Southern Ice Cap supports numerous glaciers that calve icebergs into a network of fjords along Chile's Pacific coast that come as close as 60 km to the Cerro Fitz Roy massif.



FIG. 10. The summit rime mushroom on Monte Sarmiento, Tierra del Fuego, illustrates the rough surface texture of rime mushrooms. (PHOTO: Ralf Gantzhorn)

Cerro Torre (49.29°S, 73.10°W, 3,128 m MSL), on the eastern edge of the Southern Patagonian Ice Cap in Argentina’s Los Glaciares National Park, is, like the Swiss Matterhorn, one of the iconic mountains of the world. It was long thought to be unclimbable, and has a rich climbing history. It is also the mountain with the best-known rime mushrooms. Cerro Torre and the Cerro Fitz Roy massif are the focus of the following analysis and discussion. We used two sources of meteorological data. First, a long-term combined model–observation dataset provides mean hemispheric charts at 70 kPa (700 mb) for 1989–2005 (ERA-Interim Reanalysis, Dee et al. 2011). Second, radiosonde data for 1975–2012 for three Chilean and Argentine radiosonde stations that surround Cerro Torre provide additional information about winds (Fig. 5). Analyses will focus on the 70-kPa pressure level because it is at about the same elevation as Cerro Torre’s summit.

Winds. The key feature of the Southern Patagonian climate was described in a 1953 *Journal of Glaciology* article by Dr. Louis Lliboutry of the University of Chile, a member of the 1951–52 French Alpine Expedition to the Cerro Fitz Roy area, as “the very strong and almost incessant wind, which often reaches 100 km h⁻¹ on the crests, with gusts of 150–180 km h⁻¹.”

Both high wind speeds (Eq. 1) and consistent wind directions can be seen in the mean January and July upper-air charts (Fig. 6a,b), with a circumpolar vortex extending northward over the Southern Ocean into Patagonia in both months. No strong mean troughs or ridges perturb the wind direction, indicating that



FIG. 11. Rime mushrooms form below the West Ridge route on Punta Herron, in the Cerro Fitz Roy massif of Argentine Patagonia. These overhanging mushrooms sometimes break and fall onto the rocks below. (PHOTO: Rolando Garibotti)

the mean winds are westerly. Monthly mean wind directions at 70 kPa at the three radiosonde stations (Fig. 7a) confirm that winds in Patagonia are consistently from a narrow range of westerly directions. These are some of the strongest sustained winds on Earth, which is why latitudes between 40° and 50°S are known as the “Roaring Forties.”

There are seasonal variations in wind strength, if not direction, across Patagonia. In the summer (January, Fig. 6a), a narrow band of especially strong westerly jet winds at about 55°S strikes the tip of South America. In winter (July, Fig. 6b), the height lines are distributed more evenly across the latitude zone between the edges of the Antarctic continent and 30°S, indicating more consistent wind speeds across Patagonia. Thus, summer winds are stronger than winter winds over the southern tip of South America (Fig. 7b, Punta Arenas) but weaker than winter winds at more northerly latitudes (Fig. 7b, Puerto Montt). The winds at Cerro Torre are probably somewhat stronger than indicated for the coast (Fig. 7b) because of the speedup effect, which strengthens winds as they cross a mountain barrier (note the color change over the Andes in Fig. 6). Winds probably exceed 28 m s⁻¹ (95 km h⁻¹) a significant fraction of the time.

Clouds and precipitation. The west side of the southern Andes is frequently enveloped in clouds as the cool, moist air from the coast cools and condenses to form clouds. This cloudiness is enhanced by storm systems carried around the Southern Ocean in the

circumpolar vortex. For the clouds to envelop the summits, the cloud base must form below the summit elevations. The mean monthly lifting condensation levels (LCLs) or cloud base heights at coastal stations (Fig. 8) are lowest in winter, highest in summer, but consistently below the Cerro Torre summit all year. Latitudinal interpolation between the Puerto Montt and Punta Arenas suggests that the mean monthly cloud base heights west of Cerro Torre range from about 600 m MSL in summer to 250 m MSL in winter. The low LCLs indicate that Cerro Torre is without clouds on few days. At Comodoro Rivadavia on the drier east side of the continent, the LCLs and cloud bases are much higher.

Air crests the Andes and descends and warms on the east side, forming a rain shadow. Thus, large variations in precipitation occur across the Andes at this latitude. The Pacific coast west of the Fitz Roy massif receives an estimated 4,000–5,000 mm of precipitation per year, sustaining the Southern Ice Cap and ice to fjords and to valley glaciers on both east and west sides of the Andes. In contrast, in the rain shadow Coyhaique (45.6°S, 72.1°W, 310 m MSL) and Cochrane (47.2°S, 72.6°W, 182 m MSL) receive only 1,200 and 730 mm of annual precipitation, respectively (www.meteochile.cl/climas/climas_undecima_region.html).

Supercooled cloud water. The elevations of the -2° and -10° C isotherms—the preferred temperature range for supercooled droplets—vary diurnally, seasonally, and geographically. A north–south gradient in monthly mean heights of the -2° and -10° C isotherms occurs along the west coast of South America between Puerto Montt and Punta Arenas (Fig. 9). These isotherms are highest in February and lowest in August. The -2° C isotherm ranges between 1,396 and 2,775 m MSL—well below the elevation of Cerro Torre in all months. The monthly mean altitude of the -10° C isotherm varies between 2,801 and 4,270 m MSL—above the altitude of Cerro Torre in all months except June through September. This places the summit of Cerro Torre firmly in the -2° to -10° C range, in which rime formation is favored during 8 months of the year. For comparison, at the east side of the continent, the



FIG. 12. The route to the summit of Cerro Torre from the west is completely blocked by rime mushrooms. Here, two climbers, one on top of the mushroom to the right and one on the face of the summit mushroom, are climbing Cerro Torre in 2012, a relatively dry year. (PHOTO: Colin Haley)

height of the -2° C isotherm at Comodoro Rivadavia is depressed by up to 500 m relative to Puerto Montt in summer and by several hundred meters in winter and fall.

MOUNTAINEERING CHALLENGES. Because of the persistent cloudiness and strong winds in the Patagonian Andes, climbers often spend weeks in a base camp or in the nearby town of El Chaltén waiting for good weather. Windows of good weather may be brief, forcing climbers to return to base to wait out bad weather and then to reascend known pitches to continue the climb. In the summer of 2009–10, the weather was completely uncooperative and not a single climber ascended Cerro Torre.

Forecasting good weather periods in the Cerro Fitz Roy massif is difficult because of the lack of meteorological data and the consequent difficulties in initializing and assimilating data into meteorological models. Improved Internet access from El Chaltén to large-scale weather forecasts has greatly improved the chances for successful climbs and has allowed some climbers to travel to Patagonia only when good weather is anticipated.

Once on the mountain, climbers are concerned about the anchorage, surface characteristics, and internal cohesion of rime mushrooms. The icy base



FIG. 13. Colin Haley entering the base of a 50-m-long natural tunnel through the ice mushrooms on the west face of Cerro Torre in 2005. This tunnel was used by other climbers in 2005 through 2008 or later but was absent in 2011. Reports of such tunnels date back to the mid-1980s. (PHOTO: Rolando Garibotti)

of permanent or semipermanent rime mushrooms secures them to the underlying rock. A persistent rime mushroom builds up over many weather cycles and is thus affected by seasonal and daily variations in the type and extent of temperature, cloud, precipitation, and sometimes even riming. The exterior of the mushroom is generally harder than the interior but can be brittle, friable, or unconsolidated. The internal consistency ranges from hard veins in a honeycomb-like structure to a popcorn texture or even cotton candy (Fig. 10). While mushrooms can persist for a long time, they can also fracture, causing unpredictable ice falls (Fig. 11). Because a particular rime formation is highly variable over time and space, the value of advice from previous climbers is limited.

The underlying rock and solid ice is generally unreachable for solid hand and footholds or devices to secure the climber against falls. Snow pickets can be placed in the rime, but they are often insecure.

When rime mushrooms form on summit blocks (Fig. 12), routes must go over or through them, preferably in vertical creases or gullies separating pillow-like sections. Nearly vertical tunnels sometimes form in rime mushrooms (Fig. 13) and are preferred ascent routes, as their interiors are often solid ice. It is not known how these tunnels form (they may be created between converging mushrooms), but wind clearly

helps keep the tunnels open. Where suitable natural tunnels are absent and the mushroom surface is dangerous, the climber can tunnel underneath the mushroom's surface to be better secured against falls (Fig. 14).¹

CONCLUSIONS. Rime mushrooms have never been investigated scientifically, and there are many open questions. While the Cerro Fitz Roy region of Southern Patagonia exemplifies the conditions favorable for permanent but ever-changing rime mushrooms, analysis of other areas known for rime mushrooms could help define the range of conditions suitable for their formation. Meteorologically, the airflow dynamics and microphysical aspects would be of particular interest. Further study will be limited by the remoteness of these areas and the lack of meteorological data.

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¹ In addition to rime mushrooms, simple rime on rock faces can challenge climbers. Newly deposited rime or winter rime that has not been through melt-freeze cycles can be easily cleared away. Clearing rime that has gone through one or more melt-freeze cycles is more difficult, unless it has been loosened by rising temperatures. On steep rock faces, warming air and rock may cause rime-falls. Water flowing from melting rime on a rock face may subsequently freeze in cracks or chimneys, forming verglas. This thin layer of brittle, clear ice is attached to the rock or separated from it by an air gap through which water drained as the underlying rock was heated by solar radiation or by stored heat from the rock mass.

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FIG. 14. Jorge Ackermann climbing above a tunnel/half pipe that he has dug in one of Cerro Torre's notorious mushrooms. Climbers have adapted their axes with heart-shaped or shovel-like attachments for use on rime formations to improve purchase and facilitate digging. Obviously, while digging tunnels, the lead climber should position the belayer to protect against cascades of rime ice particles and ice chunks. (Photo: Rolando Garibotti)

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