# Engineering Winter

by

**Mackenzie White**

Submitted to the Program in Comparative Media Studies / Writing in partial fulfillment of the requirements for the degree of

Master of Science in Science Writing

at the

Massachusetts Institute of Technology

September 2025



Authored by: Mackenzie White

Program in Comparative Media Studies/Writing

July 10, 2025

Certified and accepted by: Seth Mnookin

Director, Graduate Program in Science Writing

Thesis Advisor

Engineering Winter

by

Mackenzie White

Submitted to the Program in Comparative Media Studies / Writing in partial fulfillment of the requirements for the degree of Master of Science in Science Writing

ABSTRACT

As winters warm and snowfall becomes less reliable, ski resorts worldwide increasingly depend on artificial snow to stay open. Snowmaking, once a stopgap, has become the backbone of entire seasons in a sprawling choreography of pumps and pressurized mist designed to hold trails together. At resorts like Vermont's Bromley Mountain, snowmakers work through the night, drawing millions of gallons from limited reservoirs and operating within narrowing windows of cold air. What emerges is a portrait of winter in transition: less predictable, more expensive, increasingly manufactured.

The efforts to preserve winter recreation carry growing costs in energy, water, and equitable access. Many smaller, independent ski areas struggle to meet the demands of climate adaptation, while larger resorts expand their operations, widening the divide in who can afford to sustain operations. In the American West, where rivers depend heavily on snowpack melt, the spread of snowmaking ties winter recreation to a water system already under immense strain. As artificial snow becomes the norm, winter is increasingly a season bought, built, and rationed, raising the question of whether attempts to keep the season alive are accelerating the changes that threaten to erase it.

Thesis supervisor: Seth Mnookin

Title: Director, Graduate Program in Science Writing

## Engineering Winter

*As temperatures rise and snowpack declines, ski resorts scramble to make snow, exposing the fragile water systems beneath them.*

Halfway up the Barker 6 chairlift at Maine's Sunday River Resort, skiers pass through the line of fire of a battalion of snow guns that cover the resort's trails with artificial snow. Some riders try to angle themselves away from the human-made flurries, burying their faces in jackets and neck warmers. Others duck behind seatmates but find no shelter from the icy assault.

These flakes don't drift gently, as they would from a cloud. They strike, sharp and fast, driven by high-pressure nozzles firing in unison. The rumble of compressors merges with the rhythmic hiss of expelled air, drowning out the chairlift's steady drone and creating a soundscape as artificial as the precipitation. Less than a minute later, the lift's riders emerge from the fabricated storm, their jackets already caked with frost. Ice forms brittle casings around stray strands of hair, etches stubborn streaks across goggles, and seeps into base layers, instilling a chill that lingers long after the skiers reach the summit.

Beyond the reach of the snow guns, past the boundaries of groomed runs, frost-brushed grass and exposed rock surface in places once reliably blanketed in white through winter. The view— white ribbons of machine-made snow cutting through increasingly exposed terrain—has become familiar across resorts from Maine to the Alps[1]. Rising temperatures and erratic seasons have transformed artificial snow from an occasional supplement into a survival strategy[2], a manufactured stand-in for what is no longer guaranteed.

The implications of this shift stretch far beyond winter recreation. As natural snowpack declines across mountain ranges[3], the ski industry's scramble to adapt highlights the long-term changes that threaten water systems nationwide—and how, as is often the case, attempts to address the effects of climate change risk exacerbating the problem. From East Coast resorts spending millions to make up for insufficient snowfall to Western mountains that once relied exclusively on nature now investing in snowmaking, the industry is caught in a complex feedback loop, burning more energy and consuming more water from shrinking sources to compensate for the changes these activities help accelerate.

For the riders enduring the icy barrage on Barker 6, the cold is a temporary discomfort. For mountains like Sunday River, each artificial flake adds to the mounting cost of sustaining the season[4].

### The Architecture of Natural Snow

In his Caltech lab, physicist Ken Libbrecht grows artificial snowflakes that closely resemble the real deal, one at a time[5]. He begins by creating a slender ice needle inside a chilled chamber using a high-voltage electric field. Once the skeletal needle forms, he transfers it to a second chamber filled with supersaturated air, where humidity exceeds 100 percent and the temperature remains below freezing. Water vapor condenses and freezes onto the needle, and a snow crystal starts to take shape. Libbrecht observes as it fans outward into something intricate and symmetrical, its branches extending or simplifying in response to tiny changes in temperature and humidity. Each detail reflects the snow crystal's sensitivity to the environment Libbrecht creates.

Libbrecht describes crystal research as his "scientific hobby," supported primarily by sales of his snowflake photography. He studies these crystals to understand how complexity emerges from simple conditions, and what they reveal about the physics of pattern formation. Their growth illustrates fundamental physical processes that recur across nature, from fluid turbulence and mineral deposits to the structures of galaxies[6].

Libbrecht's snowflakes are artificial in origin but natural in form. His work captures what industrial snow systems cannot duplicate: individual structures shaped by the gradual interplay of cold and atmospheric moisture, where each natural crystal is a fleeting artifact of the sky.

Outside Libbrecht's lab, natural snow doesn't arrive on demand. High in the atmosphere, far above the reach of compressors and nozzles, its formation begins with a microscopic seed—a particle like dust, pollen, or soot. Water vapor in the cloud settles directly onto this particle, bypassing the liquid phase and forming ice. As the flake drifts to the ground, it gathers more vapor, growing in size and complexity. The exact form it takes—whether a photogenic, feathery dendrite or a simple hexagonal plate—depends on subtle shifts in its environment[7]. By the time it lands, each flake is a unique six-sided record of its descent, its singular geometry shaped by temperature, humidity, and turbulence. This intricate balance makes natural snow inherently unpredictable, ephemeral, and currently impossible to replicate on a large scale.

"If you want these really nice stellar crystals—the snowflakes that people think of when they think about snowflakes—they only form when the temperature is around minus 14 Celsius [7°F]," says Libbrecht. Warmer conditions tend to produce simpler, more compact crystals, while higher humidity leads to elaborate branching as water vapor quickly gathers on the flake's surface[8]. Each arm of a snowflake can grow by hundreds of microns per second; however, a shift of just a few degrees or a dip in humidity can halt its growth or distort it beyond recognition.

This structural variation also explains why snow looks and behaves the way it does after it settles on the ground. As snowflakes accumulate, their crystalline geometries form a loose network of spaces that trap air and bend light (this diffuse reflection gives snow its distinctive luminosity)[9]. Though ice crystals are transparent, natural snowfields radiate white as light filters through the jumble of crystal shapes, bouncing between facets and scattering in all directions. These same air pockets act as tiny shock absorbers and insulating chambers, giving natural powder its softness and its ability to cushion a skier's turn.

**A Season Engineered, Not Forecasted**

At resorts like Sunday River, skiing on fluffy, natural snow is an increasingly rare experience.

What spews from snow guns is a proxy, not a perfect copy. Artificial snow grips the slope where natural powder drifts, compacts where fresh flakes gently collapse, and lacks the effortless buoyancy that comes from falling thousands of feet through shifting air currents. The result is a surface that's heavier, icier, and less forgiving.

Even light reveals the substitution, playing differently across each surface. Machine-made snow, composed of near-identical frozen spheres, reflects more uniformly, producing a distinctive sheen that veteran skiers can recognize without ever setting a ski down.

That uniformity results from how the snow is produced. Snowmaking systems are built to generate large volumes of snow quickly and predictably, often under marginal conditions.

The process hinges on a critical threshold called wet-bulb temperature[10], a measure that combines air temperature and humidity to determine how efficiently water can cool through evaporation. In dry air, water evaporates more quickly, pulling heat away and allowing snow guns to work even when the air is just above freezing. When the wet-bulb temperature drops low enough, the combination of cold, dry air creates perfect conditions for machine-made snow.

But wet-bulb temperature is as much a constraint as it is a guide. When the air is too warm or too humid, water droplets don't freeze fast enough and fall as slush instead of snow. This makes timing critical. Resorts rely on real-time weather data to pinpoint the coldest hours, often running snow guns in the middle of the night or early morning when conditions are most favorable. But as winter warms and atmospheric moisture increases, these crucial wet-bulb windows are shrinking[11].

What happens during those narrowing windows depends on the design and capacity of a resort's snowmaking system[12]. Most snowmaking begins at ground level, where pressurized water is combined with compressed air and then forced through a series of fine nozzles. The air shreds the water into tiny droplets, propelling them into freezing conditions where they solidify almost instantly and fall as small, granular pellets designed for durability.

Other snow systems freeze only the outer shell of each droplet before it lands, allowing for a softer initial impact before the core solidifies, a technique that can accelerate coverage and improve surface cohesion. The result is a denser, longer-lasting snowpack, built to endure ski traffic and the warmth of the midday sun. High-efficiency models atomize water into finer droplets, maximizing the surface area exposed to cold air and boosting the likelihood of crystallization in borderline temperatures. Sensors continuously track shifts in temperature and humidity, fine-tuning water and air levels to optimize performance.

Even with optimal weather conditions and high-tech equipment, snowmaking requires varied approaches across mountain terrain. High-traffic runs need a dense, durable base that can withstand constant use, while beginner trails and areas groomed more frequently benefit from a softer surface that's easier to reshape. Snowmakers adjust water levels, air pressure, and nozzle settings to match each trail's needs, controlling the properties of the snow as it forms.

As traditional snowmaking becomes more limited by rising wet-bulb temperatures, some resorts are exploring technologies that can operate with minimal dependence on the weather. One example is TechnoAlpin's SnowFactory[13], which uses a sealed industrial refrigeration system to produce fine ice shavings that resemble packed snow. Unlike conventional methods that depend on atmospheric conditions, these systems can generate snow-like material even in 95-degree heat, effectively decoupling snow production from natural conditions.

Machines like these are transforming winter recreation across climates and continents. Indoor ski facilities now operate year-round in places like Dubai, Singapore, and cities across China, where many skiers learn the sport without ever touching natural snow[14]. Olympic venues in once-reliable snow regions now depend on manufactured snow to ensure competition-ready slopes[15]. In places like the Alps and Australia, ski towns whose identities were shaped by centuries of seasonal rhythms increasingly resemble industrial snow farms[16].

This global transformation reflects more than adaptation; it signals a fundamental reinvention of winter recreation from an experience that depends on annual environmental shifts to a commercial venture that can be assembled and sold on demand. Where activities like skiing, snowboarding, and sledding once depended on a partnership with nature, they now run on predictability and control.

That shift demands constant effort and brings rising costs in water, energy, and money[17].

**A Ski Resort Without Snow**

At Vermont's Bromley Mountain, a mid-sized ski area with just over 300 acres of terrain[18], Matt Folts, the resort's head snowmaker, knows exactly how steep those costs have become.

In response to warming temperatures and rising electricity costs, Bromley began modernizing its snowmaking system decades ago, starting with a major renovation in 1996 and a $1 million upgrade in 2000, which reduced compressed air use by 60 percent through the adoption of more efficient snow guns. In recent years, Folts and his team have focused on further reducing air demand by introducing low-energy fan guns and variable-frequency drive motors, technologies that enable the production of snow with less energy and greater control.

“We went from about 25,000 cubic feet of air down to 8,000,” Folts says. “That meant completely changing the type of snow gun we use. We’ve really focused on models that require less compressed air. Over the years, we’ve just gotten better at figuring out how to decrease needing that air.”

The results are visible each morning on his mountain, where the whir of snow guns has become the defining soundtrack of ski season. On most cold mornings, long before the first chairlift carries visitors up Bromley Mountain, a network of machines that make up one of the most comprehensive and energy-efficient snowmaking operations in New England has already deposited multiple layers of artificial snow.

Nicknamed "Sun Mountain" for its rare south-facing slopes, Bromley gets more direct sunlight than most Vermont resorts. That results in both warmer trails and softer snow, a combination that creates appealingly forgiving conditions for beginners. But these days, when artificial snow covers nearly all the resort's 47 trails, Bromley's calling card has also become its greatest vulnerability.

Folts has spent nearly two decades engineering winter on Bromley’s slopes. He knows the rhythms of the season here in a way few people do—not just how much snow falls, but how long it lasts, how it melts, how it compacts under the weight of skiers. He knows the temperatures at which different machines operate best, which trails will retain their base, and which ones will require an additional layer by February. Most of all, he's learned to adapt to a job that’s part science, part improvisation, a constant recalibration of water, air, and temperature.

The types of storms that once dropped steady powder on the mountain have grown more erratic and variable, often delivering mixed precipitation: snow at the summit, ice mid-mountain, and rain at the base. Even when snow falls as clean powder, wild temperature swings can quickly erase it, melting it into slush or freezing it into ice.

“This week, we’re looking at getting two feet of snow,” Folts says. “But there’s a threat of mixed rain in every single one of those storms. That never used to happen, where, since I was a kid, it was just going to be snow.”

Last winter, the challenge came not from warmth but from drought. January was Vermont's eighth driest since record-keeping began in 1895. By the time Bromley shut off its snowmaking system for the season on the final day of January, its primary water source—a 20-million-gallon reservoir pond[19]—had just enough water remaining for a single day’s worth of snowmaking.

That shortage doesn’t end at the reservoir’s edge. Mill Brook, the slender tributary that supplies the pond, now carries less than its ecological share. State surveys list long sections as having “artificial and insufficient flow,” with portions graded only partially or not at all supportive of fish and invertebrates[20].

Unlike larger resorts like neighboring Stratton, which spans nearly 100 trails and draws its water from a 160-million-gallon reservoir[21], Bromley doesn't have the capacity to endure prolonged dry spells without pausing snowmaking. As a result, Folts and his team constantly weigh conservation against the need for coverage. The resort’s limits were set in the 1990s, when engineers redesigned the system and calculated its water needs to the gallon. That number hasn’t changed, even as the winters around it have.

"This year, we had just enough," Folts says. "If we'd had another week of warm weather, we might have run out," he says. If Bromley’s supply had fallen short, the resort would have had no choice but to shut down snowmaking altogether.

"It was scary," Folts says. “This was a difficult year for a lot of ski areas."

Bromley's snowmaking operation delivers water from its reservoir through 15 miles of underground pipes to 500 hydrants spread across the mountain[22]. At night, when temperatures drop, Folts and his team create enormous stockpiles of snow, banking against the inevitable spring thaw.

"Come April, it'll go, and it'll go fast," Folts says. "We try to beef up as much as possible."

**Matt Folts**, head snowmaker at Bromley Mountain, stands in the resort’s snow gun field on a clear January afternoon after wrapping up snowmaking operations for the season.

By morning, towering, misshapen mounds of artificial snow litter the slopes. They sit in clusters like misplaced dunes, casting distorted shadows across the trails and transforming the landscape into alien, Dr. Seuss-like topography. Packed snow melts more slowly, so piling it high in cold snaps allows the crew to store coverage they'll need in the coming days and weeks when the sun softens the trails and machines can't keep up. Before the mountain opens, groomers will flatten the piles, spreading their frozen reserves across thinning trails.

Artificial snow, denser than natural snowfall, creates an insulating base that helps preserve the overall snowpack.

"It keeps the natural snow much longer," Folts says. "That's why even in bad years, you'll see us hanging onto coverage."

Still, artificial snow can only buy so much time. On Bromley's warmest south-facing slopes, Folts often returns midseason to rebuild runs, layering fresh snow over ground already stripped bare by the sun. And with each season, the cost of keeping trails covered inches higher.

**The Cost of Manufacturing Winter**

At many ski resorts, snowmaking is already the single largest electricity draw, requiring industrial-scale pumps to transport water uphill and high-pressure compressors to fracture it into mist before freezing. In Canada alone, artificial snow production generates roughly 130,000 tons of $CO_2$ per season[23]—the equivalent of adding 28,000 gas-powered cars to the road.

Until recently, most air compression systems on Vermont mountains ran on diesel, generating high emissions and fuel costs. Through a statewide initiative led by Efficiency Vermont, resorts like Bromley have replaced parts of that aging infrastructure with cleaner, more efficient alternatives. But upgrading a snowmaking system isn’t cheap.

Snowmaking’s price tag is now one of the leading reasons small ski areas shut down. Seasonal expenses can range from $500,000 to over $3.5 million, depending on a resort’s size, snow coverage, and operating window. Standard snow guns cost between $5,000 and $35,000 apiece. Fan guns—self-contained machines that blast snow across broad areas—can run as high as $52,000. Fully automated versions, equipped with weather sensors and remote controls, add another $10,000 to $20,000 per unit. Supporting infrastructure, including underground piping, pump houses, and water storage systems, can add millions more to the investment. The pricey technology is both a testament to engineering progress and a concession to the reality of a changing climate.

At Bromley, Folts has prioritized high-efficiency fan guns where he can, but the cost remains a constraint.

"I'd love to buy 100 of them," he says. "But that's a lot of $97 lift tickets."

For massive resorts like Colorado’s Vail Mountain, which spans over 5,000 acres and is part of a network of 38 resorts run by Vail Resorts[24], the price is significant but manageable. However, for smaller ski areas like Bromley, which lack the backing of resort conglomerates, it can be make-or-break. More than 45 U.S. ski areas have closed in the past two decades, most of them smaller, independent hills without the financial reserves to keep adapting[25]. The question is no longer whether ski resorts can make snow, but whether they can afford to keep making more[26].

"All downhill ski resorts are resorting to snowmaking," says Heather Hosterman, an environmental management and economics specialist at West Elk Consulting who focuses on climate adaptation. "That's in order to get the ski slopes open by the Christmas rush. If they don't open by then, their season isn't economically viable."

Each resort faces a version of this calculus, balancing steep energy costs, limited water, and infrastructure investments that rarely pay off in a single season[27]. At Bromley, every decision is a risk. Running the system too early or too late risks wasting money. Restarting it midseason costs roughly $20,000 in power adjustments alone, excluding the additional $1,000 per hour required for operation.

Small ski areas like Bromley have long served as the sport's entry points by offering affordable alternatives to corporate-owned mega-resorts[28]. They've offered a version of winter recreation that felt personal: run by locals, priced for locals, rooted in community[29]. But survival means constant reinvestment in infrastructure. What's vanishing isn't just skiing, but accessible, locally rooted winter recreation across diverse geographies[30].

As the season shortens and natural snow becomes less reliable, Bromley's strategy is now its lifeline and its limitation. And Bromley isn't alone. Across the country, small and mid-sized ski areas are facing a similar reality: adapt or risk closure[31].

Bromley Mountain's snowmaking pond, partially frozen on a January morning, supplies water to the resort's network of snow guns (right), which stand idle after snowmaking ended for the season. With natural snowfall increasingly inconsistent, the system is essential for covering trails in time for the winter operations.

**A Snowpack in Flux**

At 9 a.m. on a subzero January day at Montana's Bridger Bowl, chairlifts hang motionless, their steel cables stiff with hoarfrost beneath a cloudless sky. By now, the mountain would normally be waking up—skiers clicking into bindings, snowboarders stomping the snow off their boots, and the steady churn of lift cables cycling overhead. Instead, the slopes lie untouched. With wind chill plunging temperatures to minus 58 degrees Fahrenheit, the mountain has postponed opening until the afternoon.

Bridger Bowl, a nonprofit ski area just outside Bozeman, operates with a limited safety net. A few snow guns now line the base-area runs, but the rest of the mountain operates without a backup. Last year, its dependence on natural snowfall showed its limits.

"It was the worst year for skiing at Bridger that I've had since I moved here in 1988," says Karl Birkeland, a snow scientist at Montana State University. "We had barely enough snow to open and barely enough snow to operate all the way through the year."

Historically, Bridger was known for November openings and 100-day seasons. In 2024, it didn't open until January. Across Montana, snow came late, fell unevenly, and didn't last[32].

"I just didn't even think about skiing until February," says David Quammen, a writer and lifelong skier based in Bozeman, Montana. "A good year, we used to start skiing at Thanksgiving. Now, you're lucky if you can ski by Christmas. That's a big loss."

On the frozen morning, above the quiet base area, wind rips through the Bridger Range in staggered gusts, carving snow into sharp, hardened ridges along the exposed slopes. High along the peaks, ski patrollers move methodically, planting explosives in avalanche-prone chutes. Their goal isn't to stop avalanches, but to control them by triggering small, manageable slides[33]. Over time, snow builds in distinct layers: soft powder, wind slabs, brittle crusts. When dense snow accumulates over weak, granular deposits, the structure becomes unstable. A skier's weight or a sudden gust of wind can be enough to collapse the pack.

A charge detonates on a ridge above Bridger Bowl's trails. Visible fractures race through the snowpack, and a thin slab peels off, shearing away and tumbling down the mountain moments before a concussive boom rolls through the valley like thunder.

Just beyond the ski area's controlled terrain, Andrea Bruckmeier listens from the quiet of the backcountry. A graduate student from Germany at Montana State University, she's studying how snowpacks evolve in this terrain in an area undisturbed by avalanche mitigation.

She skis across a slope of deep, untouched snow and stops near a stand of trees. Unclipping her bindings, she plants her poles, pulls a collapsible shovel from her pack, and begins to dig. A one-meter snow pit reveals the winter in cross-section: a light dusting from the last storm, a thick, wind-compacted crust, and below that, a brittle band of faceted snow. Left intact, this layer of loose, angular grains forms a hidden fault line buried beneath the season's storms.

**Andrea Bruckmeier**, a PhD student studying snow and climate at Montana State University, digs a snow pit near Bridger Bowl ski area to analyze snowpack structure.

Unlike the ski patrollers a few ridgelines away, Bruckmeier isn't here to trigger slides. She's tracking what happens over time, measuring the subtle shifts that can strengthen or destabilize the pack. Some layers harden under pressure. Others degrade. Her work focuses on how rising temperatures and changing precipitation patterns are altering the behavior of avalanches and snowpacks.

One of the most concerning shifts scientists and ski patrollers are watching is the rise in wet snow avalanches[34]. These slides don't behave like the cold, dry avalanches that dominate much of the season. They're harder to predict, harder to manage, and often more destructive.

"It's important to know, do we face more dry or more wet snow avalanches?" Bruckmeier says. "Because mitigation is different. Dry avalanches can be controlled with explosives, but wet ones—those are different. That doesn't work that well, or sometimes not at all."

**Bruckmeier** records the slope angle of a snow layer during fieldwork on an unusually cold January morning in the Bridger Mountains. The data will feed into her research on how avalanche patterns are changing across the region.

Unlike dry slab avalanches, which break with speed and violence, wet avalanches tend to release more slowly. As temperatures rise, meltwater seeps through the snowpack, loosening the bonds between snow grains and layers. The snow weakens from the inside out. At first, it might slump in pieces—heavy, saturated chunks peeling off the slope. But if enough water accumulates, an entire slab can give way at once, releasing a dense, churning mass that moves like wet cement. It doesn't roar down the mountain so much as ooze, capable of dragging everything in its path.

For decades, these wet slides were primarily a late-season hazard, appearing in April or May as temperatures began to climb. They now arrive earlier, sometimes as soon as January.

"We have things happening that are completely different than anyone in that area has experienced before," Birkland says. "You can't always rely just on your experience. You need to understand the science, because we're moving into realms we don't fully understand."

Bruckmeier presses a thin thermometer into the pit wall, recording the temperature at each layer. The gradient is stark: bitterly cold at the surface, warming with depth as snow insulates itself. Through a magnifying glass, she examines the crystal structure of the weakest layer. The grains glint in the morning light, refracting the landscape into sharp, fractured pieces.

It still snows at Bridger Bowl, but the patterns that once governed its arrival and melt are changing rapidly. The layers in Bruckmeier's snow pit reveal more than avalanche risk; they catalogue the unraveling of a water system that has quietly sustained the American West for generations.

**Water in the West**

Mountain snowfields have long served as natural reservoirs, storing winter precipitation and releasing it gradually as spring temperatures rise. For much of the West, this system sustained river flow through the driest months, feeding the Colorado, Missouri, and Columbia basins with a cadence that shaped landscapes, ecosystems, and human settlements.

That rhythm is breaking down. Since 1955, April snowpack—the amount of snow present at the start of the spring melt—has declined at more than 80 percent of long-term monitoring sites across the western United States, according to the Environmental Protection Agency[35]. Losses are particularly severe in lower-elevation areas, where more winter storms now fall as rain instead of snow[36].

From where Bruckmeier stands at Bridger Bowl, every slope drains into a watershed. Some feed the Gallatin River, which joins the Missouri and eventually the Mississippi. To the south, other ranges drain into the Colorado Basin, where nearly 40 million people rely on snowmelt for drinking water, crops, and electricity[37]. The Colorado is not like rivers fed primarily by rainfall; it draws nearly 80 percent of its volume from high-elevation snowpack. That dependence makes it acutely vulnerable as winters shorten and warm[38].

Peak runoff is also arriving earlier, rushing out of the mountains before demand surges in the heat of summer[39]. Water that once descended gradually through July now floods downstream in a matter of weeks, overwhelming infrastructure before it is needed. The hydrologic pendulum swings between extremes. Flash floods are followed by prolonged drought, leaving ecosystems and infrastructure struggling to adapt.

The shortfall begins in the snowpack. Each inch lost in April means less water stored for the dry months ahead, millions of gallons that will never reach farms, cities, or hydropower systems in the months that need it most. A 2021 study projected that if greenhouse gas emissions continue at current levels, the Colorado's flow could decline by another 30 percent by mid-century[40]. Under those conditions, much of the region could enter what scientists call "snow drought," a state in which winter precipitation becomes too scarce or unpredictable to sustain rivers through the year.

Even before climate change accelerated the strain, the rules that governed the system were flawed. In 1922, during an unusually wet period, U.S. officials divided up rights to the Colorado's flow, allocating more water than the river had ever reliably carried[41]. A century later, as the basin enters its driest period in at least twelve hundred years[42], that legal foundation is collapsing. The gap between what was promised and what the river can provide now exceeds one million acre-feet each year.

The results of this disconnect are glaringly obvious. Lake Mead, in Nevada and Arizona, and Lake Powell, on the Utah–Arizona border, are the two largest reservoirs in the country. Both have retreated dramatically over the past two decades. White mineral bands trace red rock walls like bathtub rings, marking water levels from years past that are hundreds of feet above where they now stand. From above, satellite images show the reservoirs shrinking into pale, skeletal outlines—a visible record of what's been lost.

The crisis has drawn governors, federal agencies, and water managers into emergency negotiations[43]—not over whether cuts must happen, but who will absorb them. For decades, many of these same conversations excluded the people with some of the oldest rights to the river[44]. Tribal nations collectively hold legal claims to more than a quarter of the Colorado's annual flow, yet much of that water has never arrived[45]. In many cases, the infrastructure to move water to where it was promised was never even built. In others, settlements were delayed or ignored. Now, tribal governments are working to secure a meaningful role in how the river is managed and how its limits are shared[46].

At the same time, roughly 80 percent of the Colorado's diverted water goes to agriculture like lettuce fields in California, citrus groves in Arizona, and millions of acres of alfalfa, one of the thirstiest crops in the West[47]. Grown mostly for livestock, alfalfa consumes more water than all the basin's major cities combined. Though many farmers have adopted more efficient irrigation systems[48], the basic equation hasn't changed. Seven states and Mexico continue to draw legal entitlements from a river that can no longer satisfy them. Water management has become triage, an ongoing calculation of who gives up water and who gets to take it.

Even once-successful adaptation strategies are losing ground[49]. Central Arizona has long used imported Colorado River water for managed aquifer recharge, stabilizing groundwater supplies that cities and farms could draw from in dry years. But as Colorado River deliveries decline, those recharge flows are also dwindling. Without replenishment, stored groundwater will shrink, and land subsidence could return, making aquifers harder and more expensive to access, and forcing irrigators to pump from greater depths.

In the West, ski resorts have carved out a precarious place in the competition for water. Built high in mountain headwaters, they rely on the systems that downstream farms, cities, and ecosystems are struggling to preserve.

Resorts across the Rockies now draw millions of gallons from streams each season[50], turning water into frozen insurance to guarantee snowy slopes. The assumption is that what is borrowed will be returned—that when the snow melts, the water will flow back into the watershed. But in dry years, the water used at the summit doesn't always reach the valley floor[51].

What begins as an effort to protect a ski season may ultimately amplify the very losses it was meant to buffer. Research suggests that large-scale snowmaking can significantly shift the hydrology of streams and rivers[52], pushing the spring melt earlier, disrupting streamflow, and worsening shortages downstream[53]. It's a strategy that extends the season, but may come at a cost to the watershed it depends on[54].

At Bridger Bowl, snowmaking arrived only recently. For decades, the resort relied on natural snow. But in the past few seasons, the gamble has become harder to justify. A handful of guns now line the base runs, part of a broader effort that the resort may soon magnify. Bridger's proposed Master Development Plan[55] includes a major expansion of snowmaking capacity and new infrastructure to support it, citing warming winters and the need to stay competitive in a changing climate.

Public feedback on the plan has been mixed. Some see it as a smart investment in resiliency. Others worry it risks turning Bridger into a smaller version of the resort conglomerates that many locals moved to Bozeman to escape. The plan points to the familiar Western question: when the water runs short, who gets a share of the river?

"You can't make snow without water," Folts says.

In some cases, the snowmaking infrastructure has served a purpose beyond recreation. During the 2021 Caldor Fire, snow guns at a Lake Tahoe ski resort were used to spray water on buildings and vegetation as flames closed in, revealing yet another role these systems might play in a drier, more combustible future.

Now, that same machinery is back to its original task. At night, as temperatures drop, the systems hum on. Nozzles open, pressurized mist flies, and winter is rebuilt, flake by flake. The water will return, but not always when or where it's required.

**Snow's Future**

From the sunny slopes of Bromley to the halfpipes of the 2026 Winter Olympics, artificial snow keeps lifts running, slopes white, and traditions alive amid abnormally warm temperatures—at least for now.

It is a compromise, a precarious bargain with a changing climate and all it threatens to erase. Snowmaking can stretch a season, but it cannot stop the shift beneath it. Resorts refine their methods, swap old guns for newer ones, and tap into renewable energy sources where possible. But what they're building is not a season unfolding. It's a season assembled—laid down trail by trail, held together by timing, water, and luck.

On a clear afternoon in late January, Matt Folts stands at the edge of a trail at Bromley. He's wearing a black hoodie and mirrored sunglasses that catch the sun. Around him, the snow guns are silent, their job finished. The resort's reservoir is low but not empty. A season's worth of effort—water moved, hours logged, temperatures watched—has stretched winter as far as it will go. He knows they'll make it through this year. Beyond that, nothing is certain.

At Bridger Bowl, Bruckmeier climbs out of her snow pit, measurements in hand. Another avalanche charge echoes across the ridgeline. A plume of snow rises, then settles back into the quiet. She scribbles her final notes into a weatherproof field book, clicks into her bindings, and skis off toward the trees.

As snowpack thins and runoff shifts, the West faces a future unmoored from the patterns that shaped it. Winter no longer arrives as it once did. It must be made, measured, managed. In the mountains, scientists like Bruckmeier are watching the first cracks form. Below, the lifts have started to turn. A few early skiers carve fleeting lines into the soft white.

**Notes**

---

[1] Veronika Mitterwallner et al., “Global Reduction of Snow Cover in Ski Areas under Climate Change,” ed. Sher Muhammad, *PLOS ONE* 19, no. 3 (March 13, 2024): e0299735, https://doi.org/10.1371/journal.pone.0299735.

[2] Marko Joksimović et al., “Artificial Snowmaking: Winter Sports Between State-Owned Company Policy and Tourist Demand,” *Journal of Hospitality & Tourism Research* 45, no. 7 (September 2021): 1170–87, https://doi.org/10.1177/1096348020957072.

[3] “NRCS SNOTEL and Snow Course Data | Drought.Gov,” https://www.drought.gov/data-maps-tools/nrcs-snotel-and-snow-course-data.

[4] Lydia Horne et al., “Risk Perceptions of Climate Change amongst Nature-Based Tourism Stakeholders in Western Maine” (PhD Thesis, University of Maine, 2017).

[5] K Libbrecht, “SnowCrystals.Com,” Snow Crystals, https://www.snowcrystals.com/.

[6] Sofia Biagi, Chaouqi Misbah, and Paolo Politi, “Universality Classes for Unstable Crystal Growth,” 2014, https://doi.org/10.48550/ARXIV.1401.4263.

[7] Ukichiro Nakaya, *Snow Crystals: Natural and Artificial* (Harvard University Press, 1954), https://doi.org/10.4159/harvard.9780674182769.

[8] Kenneth G. Libbrecht, “Toward a Comprehensive Model of Snow Crystal Growth Dynamics: 1. Overarching Features and Physical Origins” (arXiv, 2012), https://doi.org/10.48550/ARXIV.1211.5555.

[9] Marie Dumont et al., “Experimental and Model-Based Investigation of the Links between Snow Bidirectional Reflectance and Snow Microstructure,” *The Cryosphere* 15, no. 8 (August 20, 2021): 3921–48, https://doi.org/10.5194/tc-15-3921-2021.

[10] Roland Stull, “Wet-Bulb Temperature from Relative Humidity and Air Temperature,” *Journal of Applied Meteorology and Climatology* 50, no. 11 (November 2011): 2267–69, https://doi.org/10.1175/JAMC-D-11-0143.1.

[11] David Newth and Don Gunasekera, “Projected Changes in Wet-Bulb Globe Temperature under Alternative Climate Scenarios,” *Atmosphere* 9, no. 5 (May 15, 2018): 187, https://doi.org/10.3390/atmos9050187.

[12] Nina Lintzén, *Snowmaking and Snowstorage* (Luleå tekniska universitet, 2012).

[13] Felix Michel, “When the Snow Stops : How Climate Change Impacts Alpine Competitive Advantage and Innovation” (M.S., Portugal, Universidade Catolica Portuguesa (Portugal), 2020), https://www.proquest.com/docview/2925088699/abstract/11891AAE559442D0PQ/1.

[14] “LOCATIONS,” *Indoor Snow News* (blog), February 2, 2019, https://indoorsnownews.com/blog/.

[15] Robert Steiger and Daniel Scott, “Climate Change and the Climate Reliability of Hosts in the Second Century of the Winter Olympic Games,” *Current Issues in Tourism*, September 13, 2024, 1–14, https://doi.org/10.1080/13683500.2024.2403133.

[16] Christian Rixen et al., "Winter Tourism and Climate Change in the Alps: An Assessment of Resource Consumption, Snow Reliability, and Future Snowmaking Potential," *Mountain Research and Development* 31, no. 3 (August 2011): 229–36, https://doi.org/10.1659/MRD-JOURNAL-D-10-00112.1.

[17] Jonathan Cognard et al., "The Snow Must Go on: Can Snowmaking Keep Ski Resorts Profitable in a Changing Climate?," *Current Issues in Tourism*, October 8, 2024, 1–18, https://doi.org/10.1080/13683500.2024.2409862.

[18] Bromley Mountain, "About Bromley Mountain: History and Overview," 2025, https://www.bromley.com/about/.

[19] The Daily Advertiser, "Bromley Snow Pond in Bennington County, VT," The Daily Advertiser, https://data.theadvertiser.com/dam/vermont/bennington-county/bromley-snow-pond/vt00322/.

[20] "West, Williams, Saxtons Rivers and Adjacent Connecticut River Tactical Basin Plan" (Vermont Agency of Natural Resources Department of Environmental Conservation Watershed Management Division, n.d.), https://dec.vermont.gov/sites/dec/files/wsm/docs/pl_basin11-13_draft.pdf.

[21] Robert M Sanford and Mark B Lapping, "The Beckoning Country: Act 200, Act 250 and Regional Planning in Vermont," in *Big Places, Big Plans* (Routledge, 2017), 5–27.

[22] "Snowmaking Info Blog," https://www.bromley.com/blog/snowmaking-info/.

[23] Natalie Knowles, Daniel Scott, and Robert Steiger, "Sustainability of Snowmaking as Climate Change (Mal)Adaptation: An Assessment of Water, Energy, and Emissions in Canada's Ski Industry," *Current Issues in Tourism* 27, no. 10 (May 18, 2024): 1613–30, https://doi.org/10.1080/13683500.2023.2214358.

[24] Thomas Quinn Marabello, "The Connection Between Zermatt and Vail: How a Swiss Alpine Village Influenced the Creation of a Colorado Village and Ski Resort in the Rocky Mountains," *Swiss American Historical Society Review* 61, no. 1 (2025): 4.

[25] Daniel Moscovici, "Ski Resort Closures and Opportunities for Sustainability in North America," *Land* 11, no. 4 (2022), https://doi.org/10.3390/land11040494.

[26] Jonathan Cognard et al., "Is Snowmaking Growth (F)Utile? A Dynamic Panel Data Analysis of Ski Resorts' Profitability Under Climate Change" (SSRN, 2023), https://doi.org/10.2139/ssrn.4379897.

[27] Cognard et al., "The Snow Must Go On."

[28] Michael J Sheridan and Kevin Caskey, "Competitive Strategy and Cooperation Among Smaller Ski Resorts in the Era of the Superpass," *Tourism Review International* 29, no. 2 (2025): 171–88.

[29] Jeremy K Davis, *Lost Ski Areas of Southern Vermont* (Arcadia Publishing, 2010).

[30] Lawrence C. Hamilton et al., "Warming Winters and New Hampshire's Lost Ski Areas: An Integrated Case Study," *International Journal of Sociology and Social Policy* 23, no. 10 (October 1, 2003): 52–73, https://doi.org/10.1108/01443330310790309.

[31] Moscovici, "Ski Resort Closures and Opportunities for Sustainability in North America."

[32] Natural Resources Conservation Service, “Montana Water Supply Outlook Report” (Bozeman, MT: U.S. Department of Agriculture, January 2024), https://efotg.sc.egov.usda.gov/references/public/MT/WSOR202401.pdf; USDA (U.S. Department of Agriculture) Natural Resources Conservation Service, “Snow Telemetry (SNOTEL) and Snow Course Data and Products,” 2023, https://www.drought.gov/data-maps-tools/nrcs-snotel-and-snow-course-data.

[33] Joel Juergens, “Practical Experience with Aerial Detonation of Explosives for Avalanche Control,” in *Proceedings of the 1984 International Snow Science Workshop, Aspen, Colorado*, 1984, 67–69.

[34] Nicolas Eckert et al., “Climate Change Impacts on Snow Avalanche Activity and Related Risks,” *Nature Reviews Earth & Environment* 5, no. 5 (May 2024): 369–89, https://doi.org/10.1038/s43017-024-00540-2.

[35] USDA (U.S. Department of Agriculture) Natural Resources Conservation Service, “Snow Telemetry (SNOTEL) and Snow Course Data and Products.”

[36] Philip W. Mote et al., “Dramatic Declines in Snowpack in the Western US,” *Npj Climate and Atmospheric Science* 1, no. 1 (March 2, 2018): 2, https://doi.org/10.1038/s41612-018-0012-1.

[37] Jason Robison et al., “Challenge and Response in the Colorado River Basin,” *Water Policy* 16, no. S1 (March 1, 2014): 12–57, https://doi.org/10.2166/wp.2014.003.

[38] American Rivers, “America’s Most Endangered Rivers 2023,” 2023, https://www.americanrivers.org/wp-content/uploads/2023/04/AR_2023-Most-Endangered-Rivers_lowres-3.pdf.

[39] Amy L. McCoy et al., “The Press and Pulse of Climate Change: Extreme Events in the Colorado River Basin,” *JAWRA Journal of the American Water Resources Association* 58, no. 6 (December 2022): 1076–97, https://doi.org/10.1111/1752-1688.13021.

[40] Olivia L. Miller et al., “How Will Baseflow Respond to Climate Change in the Upper Colorado River Basin?,” *Geophysical Research Letters* 48, no. 22 (2021): e2021GL095085, https://doi.org/10.1029/2021GL095085.

[41] U.S. Bureau of Reclamation, “The Colorado River Compact,” 1922, https://www.usbr.gov/lc/region/g1000/pdfiles/crcompct.pdf.

[42] A. Park Williams, Benjamin I. Cook, and Jason E. Smerdon, “Rapid Intensification of the Emerging Southwestern North American Megadrought in 2020–2021,” *Nature Climate Change* 12, no. 3 (March 2022): 232–34, https://doi.org/10.1038/s41558-022-01290-z.

[43] “Biden-Harris Administration Announces Historic Consensus System Conservation Proposal to Protect the Colorado River Basin | U.S. Department of the Interior,” Press Release, May 22, 2023, https://www.doi.gov/pressreleases/biden-harris-administration-announces-historic-consensus-system-conservation-proposal.

[44] University of New Mexico, “Native American Water Rights Settlement Project Digital Repository,” 2025, https://digitalrepository.unm.edu/nawrs/.

[45] Chris Outcalt, "The Ute Mountain Ute Can't Access Their Colorado River Water Rights. Here's How the Tribal Chairman Is Trying to Change That.," *The Colorado Sun* (blog), June 11, 2022, http://coloradosun.com/2022/06/11/ute-mountain-ute-colorado-river-tribal-chairman/.

[46] Water & Tribes Initiative, "Enhancing Tribal Capacity and Supporting Sustainable Water Use through Collaboration," 2024, https://www.waterandtribes.org/.

[47] Ben Faber, *Drought Tip: Irrigating Citrus with Limited Water* (University of California, Agriculture and Natural Resources, 2015).

[48] Gary Paul Nabhan et al., "Toward Water-Resilient Agriculture in Arizona: Future Scenarios Addressing Water Scarcity in the Lower Colorado River Basin," 2023, https://swc.arizona.edu/sites/swc.arizona.edu/files/Toward%20Water-Resilient%20Agriculture%20in%20Arizona%20Report_FINAL.pdf.

[49] Bridget R. Scanlon et al., "Multidecadal Drought Impacts on the Lower Colorado Basin with Implications for Future Management," *Communications Earth & Environment* 6, no. 1 (March 18, 2025): 214, https://doi.org/10.1038/s43247-025-02149-9.

[50] Alejandro Martinez-Berrios, "Water in the Ski Industry: A Look at the Impacts on Water Bodies," *Crested Butte*, 2017, 78.

[51] Yayi Wang, "The Impact of Snowmaking at Ski Resorts on the Local Ecosystem," *Crested Butte* 72 (2017).

[52] Molly Blakslee, "Snow Management and Local Hydrology: A Case Study at Prospect Ski Area," 2025.

[53] Samuel Morin et al., "Simulated Hydrological Effects of Grooming and Snowmaking in a Ski Resort on the Local Water Balance," *Hydrology and Earth System Sciences* 27, no. 23 (December 4, 2023): 4257–77, https://doi.org/10.5194/hess-27-4257-2023.

[54] Wang, "The Impact of Snowmaking at Ski Resorts on the Local Ecosystem."

[55] "2025 Bridger Bowl Master Development Plan," ArcGIS StoryMaps, May 23, 2025, https://storymaps.arcgis.com/collections/3c0dc28f577641ddb9a5923737723dc1.

## Bibliography


Advertiser, The Daily. “Bromley Snow Pond in Bennington County, VT.” The Daily Advertiser. https://data.theadvertiser.com/dam/vermont/bennington-county/bromley-snow-pond/vt00322/.

American Rivers. “America’s Most Endangered Rivers 2023,” 2023. https://www.americanrivers.org/wp-content/uploads/2023/04/AR_2023-Most-Endangered-Rivers_lowres-3.pdf.

ArcGIS StoryMaps. “2025 Bridger Bowl Master Development Plan,” May 23, 2025. https://storymaps.arcgis.com/collections/3c0dc28f577641ddb9a5923737723dc1.

Biagi, Sofia, Chaouqi Misbah, and Paolo Politi. “Universality Classes for Unstable Crystal Growth,” 2014. https://doi.org/10.48550/ARXIV.1401.4263.

“Biden-Harris Administration Announces Historic Consensus System Conservation Proposal to Protect the Colorado River Basin | U.S. Department of the Interior.” Press Release, May 22, 2023. https://www.doi.gov/pressreleases/biden-harris-administration-announces-historic-consensus-system-conservation-proposal.

Blakslee, Molly. “Snow Management and Local Hydrology: A Case Study at Prospect Ski Area,” 2025.

Bromley Mountain. “About Bromley Mountain: History and Overview,” 2025. https://www.bromley.com/about/.

Cognard, Jonathan, Lucas Berard-Chenu, Yves Schaeffer, and Hugues François. “Is Snowmaking Growth (F)Utile? A Dynamic Panel Data Analysis of Ski Resorts’ Profitability Under Climate Change.” SSRN, 2023. https://doi.org/10.2139/ssrn.4379897.

———. “The Snow Must Go on: Can Snowmaking Keep Ski Resorts Profitable in a Changing Climate?” *Current Issues in Tourism*, October 8, 2024, 1–18. https://doi.org/10.1080/13683500.2024.2409862.

Davis, Jeremy K. *Lost Ski Areas of Southern Vermont*. Arcadia Publishing, 2010.

Dumont, Marie, Frederic Flin, Aleksey Malinka, Olivier Brissaud, Pascal Hagenmuller, Philippe Lapalus, Bernard Lesaffre, et al. “Experimental and Model-Based Investigation of the Links between Snow Bidirectional Reflectance and Snow Microstructure.” *The Cryosphere* 15, no. 8 (August 20, 2021): 3921–48. https://doi.org/10.5194/tc-15-3921-2021.

Eckert, Nicolas, Christophe Corona, Florie Giacona, Johan Gaume, Stephanie Mayer, Alec van Herwijnen, Pascal Hagenmuller, and Markus Stoffel. “Climate Change Impacts on Snow Avalanche Activity and Related Risks.” *Nature Reviews Earth & Environment* 5, no. 5 (May 2024): 369–89. https://doi.org/10.1038/s43017-024-00540-2.

Faber, Ben. *Drought Tip: Irrigating Citrus with Limited Water*. University of California, Agriculture and Natural Resources, 2015.

Hamilton, Lawrence C., David E. Rohall, Benjamin C. Brown, Gregg F. Hayward, and Barry D. Keim. “Warming Winters and New Hampshire’s Lost Ski Areas: An Integrated Case Study.” *International Journal of Sociology and Social Policy* 23, no. 10 (October 1, 2003): 52–73. https://doi.org/10.1108/01443330310790309.

Horne, Lydia, Sandra De Urioste-Stone, John Daigle, and Caroline Noblet. “Risk Perceptions of Climate Change amongst Nature-Based Tourism Stakeholders in Western Maine.” PhD Thesis, University of Maine, 2017.

Indoor Snow News. “LOCATIONS,” February 2, 2019. https://indoorsnownews.com/blog/.

Joksimović, Marko, Mirjana Gajić, Snežana Vujadinović, Jelena Milenković, and Vladimir Malinić. "Artificial Snowmaking: Winter Sports Between State-Owned Company Policy and Tourist Demand." *Journal of Hospitality & Tourism Research* 45, no. 7 (September 2021): 1170–87. https://doi.org/10.1177/1096348020957072.

Juergens, Joel. "Practical Experience with Aerial Detonation of Explosives for Avalanche Control." In *Proceedings of the 1984 International Snow Science Workshop, Aspen, Colorado*, 67–69, 1984.

Knowles, Natalie, Daniel Scott, and Robert Steiger. "Sustainability of Snowmaking as Climate Change (Mal)Adaptation: An Assessment of Water, Energy, and Emissions in Canada's Ski Industry." *Current Issues in Tourism* 27, no. 10 (May 18, 2024): 1613–30. https://doi.org/10.1080/13683500.2023.2214358.

Libbrecht, K. "SnowCrystals.Com." Snow Crystals. https://www.snowcrystals.com/.

Libbrecht, Kenneth G. "Toward a Comprehensive Model of Snow Crystal Growth Dynamics: 1. Overarching Features and Physical Origins." arXiv, 2012. https://doi.org/10.48550/ARXIV.1211.5555.

Lintzén, Nina. *Snowmaking and Snowstorage*. Luleå tekniska universitet, 2012.

Marabello, Thomas Quinn. "The Connection Between Zermatt and Vail: How a Swiss Alpine Village Influenced the Creation of a Colorado Village and Ski Resort in the Rocky Mountains." *Swiss American Historical Society Review* 61, no. 1 (2025): 4.

Martinez-Berrios, Alejandro. "Water in the Ski Industry: A Look at the Impacts on Water Bodies." *Crested Butte*, 2017, 78.

McCoy, Amy L., Katharine L. Jacobs, Julie A. Vano, J. Keaton Wilson, Season Martin, Angeline G. Pendergrass, and Rob Cifelli. "The Press and Pulse of Climate Change: Extreme Events in the Colorado River Basin." *JAWRA Journal of the American Water Resources Association* 58, no. 6 (December 2022): 1076–97. https://doi.org/10.1111/1752-1688.13021.

Michel, Felix. "When the Snow Stops : How Climate Change Impacts Alpine Competitive Advantage and Innovation." M.S., Universidade Catolica Portuguesa (Portugal), 2020. https://www.proquest.com/docview/2925088699/abstract/11891AAE559442D0PQ/1.

Miller, Olivia L., Matthew P. Miller, Patrick C. Longley, Jay R. Alder, Lindsay A. Bearup, Tom Pruitt, Daniel K. Jones, Annie L. Putman, Christine A. Rumsey, and Tim McKinney. "How Will Baseflow Respond to Climate Change in the Upper Colorado River Basin?" *Geophysical Research Letters* 48, no. 22 (2021): e2021GL095085. https://doi.org/10.1029/2021GL095085.

Mitterwallner, Veronika, Manuel Steinbauer, Gregor Mathes, and Anna Walentowitz. "Global Reduction of Snow Cover in Ski Areas under Climate Change." Edited by Sher Muhammad. *PLOS ONE* 19, no. 3 (March 13, 2024): e0299735. https://doi.org/10.1371/journal.pone.0299735.

Morin, Samuel, Hugues François, Marion Réveillet, Eric Sauquet, Louise Crochemore, Flora Branger, Étienne Leblois, and Marie Dumont. "Simulated Hydrological Effects of Grooming and Snowmaking in a Ski Resort on the Local Water Balance." *Hydrology and Earth System Sciences* 27, no. 23 (December 4, 2023): 4257–77. https://doi.org/10.5194/hess-27-4257-2023.

Moscovici, Daniel. "Ski Resort Closures and Opportunities for Sustainability in North America." *Land* 11, no. 4 (2022). https://doi.org/10.3390/land11040494.

Mote, Philip W., Sihan Li, Dennis P. Lettenmaier, Mu Xiao, and Ruth Engel. "Dramatic Declines in Snowpack in the Western US." *Npj Climate and Atmospheric Science* 1, no. 1 (March 2, 2018): 2. https://doi.org/10.1038/s41612-018-0012-1.

Nabhan, Gary Paul, Brian D Richter, Erin C Riordan, and Catherine Tornbom. "Toward Water-Resilient Agriculture in Arizona: Future Scenarios Addressing Water Scarcity in the Lower Colorado River Basin," 2023. https://swc.arizona.edu/sites/swc.arizona.edu/files/Toward%20Water-Resilient%20Agriculture%20in%20Arizona%20Report_FINAL.pdf.

Nakaya, Ukichiro. *Snow Crystals: Natural and Artificial*. Harvard University Press, 1954. https://doi.org/10.4159/harvard.9780674182769.

Natural Resources Conservation Service. "Montana Water Supply Outlook Report." Bozeman, MT: U.S. Department of Agriculture, January 2024. https://efotg.sc.egov.usda.gov/references/public/MT/WSOR202401.pdf.

Newth, David, and Don Gunasekera. "Projected Changes in Wet-Bulb Globe Temperature under Alternative Climate Scenarios." *Atmosphere* 9, no. 5 (May 15, 2018): 187. https://doi.org/10.3390/atmos9050187.

"NRCS SNOTEL and Snow Course Data | Drought.Gov." https://www.drought.gov/data-maps-tools/nrcs-snotel-and-snow-course-data.

Outcalt, Chris. "The Ute Mountain Ute Can't Access Their Colorado River Water Rights. Here's How the Tribal Chairman Is Trying to Change That." *The Colorado Sun* (blog), June 11, 2022. http://coloradosun.com/2022/06/11/ute-mountain-ute-colorado-river-tribal-chairman/.

Rixen, Christian, Michaela Teich, Corina Lardelli, David Gallati, Mandy Pohl, Marco Pütz, and Peter Bebi. "Winter Tourism and Climate Change in the Alps: An Assessment of Resource Consumption, Snow Reliability, and Future Snowmaking Potential." *Mountain Research and Development* 31, no. 3 (August 2011): 229–36. https://doi.org/10.1659/MRD-JOURNAL-D-10-00112.1.

Robison, Jason, Katja Bratrschovsky, Jaime Latcham, Eliza Morris, Vanessa Palmer, and Arturo Villanueva. "Challenge and Response in the Colorado River Basin." *Water Policy* 16, no. S1 (March 1, 2014): 12–57. https://doi.org/10.2166/wp.2014.003.

Sanford, Robert M, and Mark B Lapping. "The Beckoning Country: Act 200, Act 250 and Regional Planning in Vermont." In *Big Places, Big Plans*, 5–27. Routledge, 2017.

Scanlon, Bridget R., Donald R. Pool, Ashraf Rateb, Brian Conway, Kathryn Sorensen, Bradley Udall, and Robert C. Reedy. "Multidecadal Drought Impacts on the Lower Colorado Basin with Implications for Future Management." *Communications Earth & Environment* 6, no. 1 (March 18, 2025): 214. https://doi.org/10.1038/s43247-025-02149-9.

Sheridan, Michael J, and Kevin Caskey. "Competitive Strategy and Cooperation Among Smaller Ski Resorts in the Era of the Superpass." *Tourism Review International* 29, no. 2 (2025): 171–88.

"Snowmaking Info Blog." https://www.bromley.com/blog/snowmaking-info/.

Steiger, Robert, and Daniel Scott. "Climate Change and the Climate Reliability of Hosts in the Second Century of the Winter Olympic Games." *Current Issues in Tourism*, September 13, 2024, 1–14. https://doi.org/10.1080/13683500.2024.2403133.

Stull, Roland. "Wet-Bulb Temperature from Relative Humidity and Air Temperature." *Journal of Applied Meteorology and Climatology* 50, no. 11 (November 2011): 2267–69. https://doi.org/10.1175/JAMC-D-11-0143.1.

University of New Mexico. "Native American Water Rights Settlement Project Digital Repository," 2025. https://digitalrepository.unm.edu/nawrs/.

U.S. Bureau of Reclamation. "The Colorado River Compact," 1922. https://www.usbr.gov/lc/region/g1000/pdfiles/crcompct.pdf.

USDA (U.S. Department of Agriculture) Natural Resources Conservation Service. "Snow Telemetry (SNOTEL) and Snow Course Data and Products," 2023. https://www.drought.gov/data-maps-tools/nrcs-snotel-and-snow-course-data.

Wang, Yayi. "The Impact of Snowmaking at Ski Resorts on the Local Ecosystem." *Crested Butte* 72 (2017).

Water & Tribes Initiative. "Enhancing Tribal Capacity and Supporting Sustainable Water Use through Collaboration," 2024. https://www.waterandtribes.org/.

"West, Williams, Saxtons Rivers and Adjacent Connecticut River Tactical Basin Plan." Vermont Agency of Natural Resources Department of Environmental Conservation Watershed Management Division, n.d. https://dec.vermont.gov/sites/dec/files/wsm/docs/pl_basin11-13_draft.pdf.

Williams, A. Park, Benjamin I. Cook, and Jason E. Smerdon. "Rapid Intensification of the Emerging Southwestern North American Megadrought in 2020–2021." *Nature Climate Change* 12, no. 3 (March 2022): 232–34. https://doi.org/10.1038/s41558-022-01290-z.