Cold-Air-Pool Structure and Evolution in a Mountain Basin: Peter Sinks, Utah

A Plain-Language Summary of Clements, Whiteman & Horel (2003), Journal of Applied Meteorology, Vol. 42, 752–768

Why This Study Was Done

On calm, clear nights, mountain valleys and basins fill with pools of cold, dense air. In a *valley*, the cooling is self-limiting: cold air drains away down-valley, and potentially warmer air sinks in from above to replace it, acting as a brake on how cold the valley can get. A fully *enclosed basin* has no down-valley escape route, so that brake is missing and the air can cool much further. This is why basins routinely record lower minimum temperatures than nearby valleys — yet, at the time of this study, very few field campaigns had actually measured what happens inside a truly closed basin at night.

Peter Sinks was close to a perfect natural laboratory for the question: it is small, topographically simple, nearly sealed, and famously cold. It holds Utah's all-time minimum temperature record of −56°C (−69°F) and produced the second-coldest temperature ever recorded in the contiguous United States. Beyond scientific curiosity, cold pools trap air pollution during many wintertime episodes in the western U.S. and are among the most difficult local phenomena for weather forecasters to predict, so a better physical understanding has real practical value.

The Setting: Geography of the Peter Sinks Basin

Peter Sinks is an oval limestone sinkhole about 1 km across, sitting on the crest of the Bear River Range in northern Utah. The basin floor lies at 2,500 m (≈8,200 ft) elevation, ringed by terrain rising up to about 150 m above it. Because it sits on the range crest rather than partway down a drainage, it has no tributary valleys feeding into it — an unusually clean setup for isolating basin-cooling physics.

The two lobes

The sinkhole is not a single bowl: it consists of **two lobes** — a northern lobe and a southern lobe — separated by a low pass. All experiments were conducted in the **northern lobe**. A meteorological tower was placed on the pass between the lobes specifically to test whether cold air sloshed from one lobe into the other during the night; observations there showed little near-surface transport.

Slopes, surface, and the “vegetation inversion”

- **Eastern slope:** gentlest, about 11°, covered in short grasses and sagebrush. Most instruments were placed along this slope.
- **Northern slope:** about 13°, sparse sagebrush and small shrubs.
- **Western slope:** much steeper at about 28°, with talus (loose rock) on its lower half and short conifers above; it was not instrumented because of poor access.

- **Basin floor:** very short grass and bare soil of loose clay and sandy alluvium, grazed in summer by cattle and sheep.

The basin displays a striking **"vegetation inversion"**: trees grow on the rim and upper slopes but are entirely absent from the lowest elevations — the mirror image of a normal mountainside tree line. The repeated extreme cold at the bottom is simply too harsh for trees, a living record of the cold pools this study set out to measure.

Spillover points: where the "bowl" leaks

The basin is **completely enclosed only up to 35 m above its floor**. Above that height, gaps open in the rim, and these openings control how deep the cold pool can grow — much as notches in the rim of a bowl set the level at which water overflows:

Feature	Height above floor	Significance
Full enclosure limit	35 m	Below this level the basin is completely sealed; air cooled here has no escape route.
South Gap	35 m (lowest gap)	The pass between the basin's two lobes; the first spillover point as the cold pool deepens. A tower (T9) was placed here to check whether cold air was exchanged between the lobes.
East Saddle	55 m	A low saddle on the eastern rim; a second outlet for cooled air. Tower T5 sat near this gap. Wind-scoured snowfields and large cornices in its lee attest to habitually strong winds crossing the rim.
Mean crest height	88 m	The average rim elevation and the effective "brim" of the container; the cold-pool stable layer stopped deepening at roughly this height.
Maximum relief	~150 m	Highest surrounding terrain; the entire nocturnal inversion was confined within this relief.

The total drainage area of the basin is 2.25 km^2 and its total air volume is 0.25 km^3; at the mean crest height, the enclosed volume is about 0.1 km^3. The authors argue that once the cold pool deepens to gap level, chilled air begins draining out through the gaps (requiring warmer air to sink in near the rim to replace it), and that this overflow helps explain both why the cold pool stops deepening at roughly the effective basin height and why the basin's overall cooling rate slows as the night progresses.

How the Study Was Conducted

A field campaign ran 8–12 September 1999 under ideal conditions: no precipitation, clear nights, very dry soil and air, and no fog or dew. The instrumentation comprised:

- **Three tethered balloons (tethersondes)** arranged up the fall line of the eastern slope — one on the basin floor (TS1), one mid-slope (TS2), one upper slope (TS3) — making simultaneous, coordinated vertical profiles of temperature, humidity, and wind every 20–60 minutes.
- **Nine 3-m meteorological towers** in lines up the eastern and northern slopes, plus the tower in the South Gap.
- **Thermocouple masts** (12 m tall) on both slopes, and a short 4-m mast placed in a small sub-sinkhole on the basin floor to capture the very coldest air.
- **A surface energy-budget station** on the basin floor, pairing a net radiometer (measuring radiative energy gain/loss) with a 3-D sonic anemometer (measuring turbulent heat exchange between the ground and the air).

Three experiments were run. **EXP1** (night of 8–9 Sept) enjoyed nearly ideal calm conditions and is the heart of the paper. **EXP2** (10 Sept) was cut short when ridge-top winds rose to 5–6 m/s and destroyed the developing cold pool. **EXP3** (11–12 Sept) followed a gusty afternoon that delayed inversion formation by about an hour.

What Happens on a Calm Night

On the undisturbed night, the basin floor swung through a temperature range of nearly 30°C in 24 hours, and by sunrise the air at the floor was 16°C colder than air only 55 m higher on the slope — an extraordinary inversion for such a small height difference.

The night-time atmosphere organized itself into a persistent **two-layer structure**:

- **Cold-pool stable layer (CPSL):** the frigid lower layer filling the bottom ~75 m of the basin. It grew to full depth within only 2–3 hours of sunset, then stopped deepening — but the air inside it kept getting colder all night long.
- **Capping inversion layer (CIL):** an extraordinarily sharp temperature jump — up to 17 K — sitting on top of the CPSL like a lid, from roughly 75 to 120 m above the floor. Its top corresponded approximately to the highest rim elevations. This abrupt "bluff-like" cap is unlike valleys, where temperature blends gradually into the free air aloft.

Once the cap formed, winds inside the basin essentially died — speeds fell below 0.4 m/s and lost any consistent direction. The basin air became a stagnant, isolated pool, effectively disconnected from the (much warmer) atmosphere surrounding the basin at the same elevations — and yet it continued cooling until dawn.

The Surprising Findings

The textbook "slope-flow convergence" model holds that air cools against the sidewalls, slides downhill as drainage flow, and converges over the basin bottom, deepening and chilling the pool. The Peter Sinks observations contradicted that picture in several ways:

- **Downslope flows were minor and short-lived.** Thin (<10 m), weak (<0.5 m/s) drainage currents did form on the slopes early in the evening — with one brief surge reaching 1.6 m/s — but they detached from the slopes and glided out over the basin center on top of the pre-existing shallow stable layer, and within about two hours of sunset they had faded to a 1–2 m-deep skin of air creeping at 0.2–0.3 m/s (measured by tossing dust into the air and timing its drift). The basin kept cooling long after these flows died, so drainage flow cannot be the main cooling mechanism. Moreover, the observed slope flows were entirely contained within the cold pool itself, so they were not importing new cold air from above it.
- **Air over the slopes became WARMER than air over the basin center.** At any given altitude below the cap, air above the sidewalls grew progressively warmer than air over the basin middle — by up to 5 K at sunrise — except within a razor-thin 1–2 m layer hugging the ground. This is backwards from what the convergence theory requires (cold air over the slopes is what drives drainage flow), and it explains why the downslope flows shut off.
- **A turbulent, unstable layer inside one of Earth's most stable air masses.** Just beneath the cap, a persistent 5–25 m-deep sublayer with superadiabatic (convectively unstable) temperature structure appeared — something never before reported. The authors propose it is driven by "negative convection": air chilled at the top of the layer becomes dense and sinks, overturning the layer from above, the upside-down analogue of daytime thermals rising off hot ground. This churning may help carry heat upward out of the cold pool, sustaining its all-night cooling.
- **A puzzle in the energy budget.** In the early evening the basin atmosphere lost heat at 80–90 W/m^2 — nearly matching the longwave radiation escaping the ground surface — yet turbulent heat transfer at the floor collapsed to essentially zero shortly after sunset, while the air kept cooling (at ever-slower rates, down to just a few W/m^2 by dawn). The authors conclude that direct radiative cooling of the air itself (radiative flux divergence) must take over as the dominant mechanism once the basin goes still — a process the surface-focused conventional theory does not capture.

The Role of Wind Above the Basin

Everything above describes calm nights. When ridge-top winds exceeded roughly 4–6 m/s, warm air mixed down into the basin: cooling was sharply curtailed, warming bursts punctuated the night, and on 10–11 September a partially built cold pool was destroyed outright around midnight. Windy-night behavior looked much more like an ordinary valley inversion — slower, steadier growth, no sharp cap, and a near-constant (and lower) rate of heat loss. Notably, the wind-scoured snowfields and cornices near the East Saddle indicate that strong winds are the norm at this exposed crest-line site; the calm conditions of EXP1 that permit record-setting cold are the exception.

Conclusions and Significance

- Enclosed basins really do behave differently from valleys: with drainage and advective exchange minimized, Peter Sinks cooled rapidly into a stagnant two-layer cold pool confined entirely within the basin's 150 m relief.

- The classical slope-flow convergence model of cold-pool growth failed in exactly the setting where it should have been cleanest. Slope drainage played only a brief, minor role.
- Continued night-long cooling must instead be driven by turbulent heat-flux divergence early in the evening, giving way to radiative flux divergence (the air radiating heat away directly) once the basin goes calm — a hypothesis the authors planned to test with radiative transfer modeling.
- The newly documented elevated turbulent (superadiabatic) sublayer, and the relative warming of air over the sidewalls, are genuinely new phenomena that raise fresh research questions about basin meteorology.
- Practically, the results bear on forecasting cold-pool formation and dissipation — one of the hardest problems in western U.S. weather prediction — and on understanding the stagnant pools that trap wintertime air pollution.

Speculative Extension: How the Record-Setting Deep-Winter Extremes Likely Happen

Note: This section goes beyond the paper. The 1999 campaign was deliberately conducted in September under dry, snow-free conditions to isolate the "pure" cold-pool mechanics. The −56°C state record (1 February 1985) is cited only as motivation, and winter conditions are not analyzed. What follows is an informed extrapolation of the study's findings to the deep-winter, snow-covered, arctic-air-mass scenario in which the records actually occur.

Start from a colder baseline. In September, the basin started near +20°C and its ~30°C diurnal swing took the floor to about −8°C. The record required the starting air mass itself to be brutally cold. A stagnant arctic high delivers exactly that — air aloft at perhaps −25 to −30°C. The basin's cooling machinery then subtracts its 25–30°C on top of that baseline; the mechanism need not change in winter, it just needs colder raw material.

Snow as a near-perfect radiator. Snow is visually white, but in the thermal infrared it behaves almost as a perfect blackbody (emissivity ≈0.98–0.99), shedding longwave radiation about as efficiently as any natural surface can. Meanwhile its high visible albedo (~0.8–0.9 when fresh) rejects most of the weak winter sun during the short day, so the basin banks almost no daytime heat to give back at night. In September, bare soil absorbed solar energy all day, and that stored ground heat conducted back up to the surface all night, partially resupplying the radiating skin. Snow removes that resupply twice over.

Snow as an insulator. Fresh snow has very low thermal conductivity — comparable to foam insulation — so the radiating surface is thermally decoupled from the relatively warm, heat-rich ground beneath it. Unable to draw on the soil's heat reservoir, the snow-surface temperature crashes far below what bare ground could reach, and the air in contact with it follows. The study measured a 7°C drop in just the lowest 2 m over bare slopes; over snow, this near-surface deficit would be substantially deeper.

Crystal form and the quality of the snow. Not all snow insulates and reflects equally, and snow arriving with an arctic frontal passage is close to the best case. Snow grown in the dendritic zone (roughly −12 to −18°C) produces branched, feathery crystals that interlock poorly and settle at 30–80 kg/m³ — mostly air by volume. Colder post-frontal snow grows as plates, columns, and bullet rosettes rather than dendrites, but packs just as badly. Either way, the snow that lands ahead of a building arctic high is low-density, high-surface-area, and — critically — undisturbed. Three consequences follow, of very unequal size.

Albedo — a large real effect. Snow albedo is governed by grain size, or equivalently specific surface area (SSA). Fresh fine-grained snow runs 60–150 m²/kg; after a few days of settling and rounding it falls to 10–20 m²/kg. A photon entering the pack must cross many ice–air interfaces before it can be absorbed, and small crystals shorten its path through ice and send it back out. The difference concentrates in the near-infrared — about half the sun's energy — where ice absorbs weakly: broadband albedo is 0.85–0.90 for fresh snow versus 0.65–0.75 for aged or wind-packed snow. With a solar-noon elevation of only ~25–30° in midwinter and partial rim shadowing through the short day, fresh powder drives absorbed solar energy in the basin to nearly nil.

Insulation — the largest effect, and the real payoff of low density. Thermal conductivity of snow scales steeply with density. At 50–100 kg/m³ (fresh powder) it is roughly 0.03–0.07 W/m·K, comparable to fiberglass batting; wind-packed or settled snow at 300–400 kg/m³ runs 0.2–0.4, five to ten times higher. It is specifically uncompacted new snow that severs the radiating surface from the ground's heat reservoir. The basin's own geometry helps: the same enclosure that seals cold air below 35 m also shelters the floor from the crest winds that scour and wind-slab the rim, so the floor can retain low-density snow while the East Saddle is being stripped.

Infrared emission — right in direction, negligible in size. It is natural to expect that more crystal surface area should also make snow a better emitter. In practice snow is already at the ceiling: at thermal-infrared wavelengths ice is strongly absorbing, so even a thin crystal layer is optically thick and emissivity holds at 0.98–0.99 regardless of grain size. Fine fresh snow may edge out coarse melt-refrozen snow by about a percent, and grain size matters somewhat more at grazing view angles, but there is essentially nowhere to go past a blackbody. The gain from powder lies not in how well the surface radiates, but in how little heat can reach it from below to replace what it radiates.

Two feedbacks the cold pool builds for itself. Once the surface begins to crash, the top few centimetres of snowpack develop temperature gradients that can exceed 100 K/m — far past the threshold for kinetic (faceted) crystal growth. The product is depth hoar: coarse, cup-shaped, poorly bonded crystals with conductivity lower still than the snow they replaced. Separately, on calm clear nights with a vapor supply, surface hoar grows as feathery crystals of near-zero density, adding a further insulating and highly reflective skin. Both are consequences of extreme cooling, and both make the following night's cooling easier.

A possible brake. The 1999 campaign explicitly had no fog or dew. In deep winter the ultimate limit on radiative cooling at sites like this is often ice fog or diamond dust: once stagnant basin air reaches ice saturation, crystals nucleate in the air itself, releasing latent heat and — more importantly — interposing an emitting layer between the surface and the cold sky, raising downwelling longwave. Whether Peter Sinks reaches that point on record nights would be worth checking against the USU sensor records and any visual observations from the basin.

A note on sequencing. Snowfall and record cold are in mild tension: snow requires cloud and usually wind, while the record requires clear skies and calm. The recipe is therefore sequential — frontal snow first, then the arctic high builds in behind it with clearing and calm before the fresh powder can be wind-packed. Both the Peter Sinks record (1 February 1985) and the contiguous-U.S. record at Rogers Pass, Montana (January 1954) fit that pattern.

A drier, weaker "sky blanket." The basin cools through the imbalance between outgoing surface emission and downwelling infrared from the atmosphere. Arctic air is extremely dry, and at 2,500 m there is simply less atmosphere overhead; both slash the downwelling longwave and widen the net radiative deficit. The study noted that the warm sidewalls and the warm capping air radiate back down toward the floor and slow its cooling — but in deep winter, snow-covered sidewalls are themselves frigid, so even that compensating term shrinks.

More hours to do it — but only one night's worth. At this latitude a September night offers about 11 hours of cooling; late January offers 14–15, and the study showed the cooling rate decays through the night (83 W/m² near sunset to under 10 W/m² after midnight) but never reaches zero. One might suppose the cold pool also carries over from night to night under a stagnant high — but routine monitoring of the basin and rim sensors (Utah State University data) shows that basin and rim temperatures converge shortly after sunrise virtually every day, even in winter. The pool mixes out daily; there is essentially no multi-day carryover in the air itself. Each record-setting night must therefore be built from scratch within a single long darkness — which makes the extremes more impressive, not less. What a persistent arctic high does contribute is persistence of the ingredients: the frigid, dry air mass aloft and the calm, clear conditions that let the machinery run unimpeded night after night.

Everything the study found still applies — amplified. The gap-controlled pool depth, the stagnant decoupled stable layer, the sharp capping inversion, and the transition to radiative flux divergence as the dominant cooling pathway all carry over. If anything, the extreme stability over snow suppresses the residual turbulent fluxes even faster, pushing the basin into the pure-radiative regime earlier in the night.

The speculative recipe for −56°C, then: an arctic air mass (cold, dry baseline) + snowpack (near-blackbody emitter, solar reflector, ground insulator) + a long winter night + calm, clear conditions + the basin's demonstrated ability to isolate and radiatively drain its own air volume — all accomplished within a single night, since the pool mixes out each morning. The September study characterized the engine; deep winter supplies premium fuel and removes every brake.

Visiting the Basin: Features from the Study You Can See on the Ground

For a September visit to the basin, several locations from the study make natural stops:

- **The basin floor and low point:** site of the tethersonde TS1, tower T1, and the energy-budget station. The very coldest air collects in a small sub-sinkhole on the floor — the study placed a 4-m thermocouple mast (TM1) there, about 24 m below the main floor datum — so the true low point is this depression within the floor, not the floor generally.

- **The vegetation inversion:** visible at a glance from the rim — conifers on the crest, sagebrush and grass midslope, and no trees at all in the bottom. It is the living map of where the cold pool sits.
- **South Gap (~35 m above the floor):** the pass between the two lobes and the lowest spillover point — tower T9 stood here. Standing in the gap, you are at the level where the deepening cold pool first begins to leak into the south lobe.
- **East Saddle (~55 m):** the second outlet, on the eastern rim near tower T5. Look for wind-scoured terrain and, in early season, cornice remnants in its lee — the evidence the authors cited that strong crest winds are the norm here.
- **The eastern slope instrument line:** the tethersonde and tower line ran up the fall line of the gentle (~11°) eastern slope from the floor to the rim — the same transect along which the detached downslope jets and the surprising sidewall warming were documented.
- **A timing tip:** the study's most dramatic action — downslope flows forming, then detaching and dying, and the inversion snapping into place — happens in the first 2–3 hours after sunset on a clear, calm evening. An evening visit with a thermometer at rim and floor can reproduce the paper's headline contrast: by morning the floor ran 16°C colder than a site only 55 m higher.

Source: Clements, C. B., C. D. Whiteman, and J. D. Horel, 2003: Cold-Air-Pool Structure and Evolution in a Mountain Basin: Peter Sinks, Utah. J. Appl. Meteor., 42, 752–768. Field campaign: 8–12 September 1999.