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Data were obtained from the ARM User Facility, a DOE Office of Science user facility managed by the Biological and Environmental Research Program.

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Recognition of external support for SALVO field campaign contributors

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Maxar WorldView imagery was supplied by Dr. David Shean from the University of Washington through NGA EnhancedView and EOCL contracts

Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement
Co-I	Co-Investigator
DOE	U.S. Department of Energy
NSA	North Slope of Alaska
PI	principal investigator
SALVO	Snow ALbedo eVOlution

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1.0 Summary

The springtime surface-albedo transition in the Alaskan Arctic, along with the forces that determine its duration and nature, was the focus of the Snow ALbedo eVOlution (SALVO) campaign.

The SALVO team investigated the reasons and durations of the stages of spring melt, during which albedo values decrease from 0.8 to 0.1, signifying the year's largest and most significant radiative energy change. SALVO II (2022, 2024) built on findings from the successful SALVO I (2019) melt season campaign and previous research on the melt transition period conducted by Grenfell and Perovich (2004). SALVO utilized the ARM NSA observatory, thus aligning with a core principle of the Atmospheric Radiation Measurement (ARM) User Facility Decadal Vision to "provide comprehensive and impactful field measurements to support scientific advancement of atmospheric process understanding."

SALVO fieldwork was conducted in the spring near the ARM NSA Central Facility in Utqiagvik, Alaska (Figure 1). Comprehensive datasets were collected in 2019, 2022, and 2024, which included spectral and broadband albedos, snow and meltwater depths, snow stratigraphy, snow grain size data, and aerial imagery. In April of each project year, before the snow began to melt, we established survey lines at three or four locations: inland tundra at NSA E12, coastal tundra at the NSA C1 site, Elson Lagoon, and offshore on the Chukchi Sea sea ice (2022 only). We set up a 200-meter-long line, marked every 5 meters, to enable repeated measurements of surface albedo and snow depth at each location. During most site visits, the SALVO II team dug at least one snow pit to assess the characteristics of the vertical snow layers, including the types and sizes of snow grains, snow density, and the distribution of liquid water. We evaluated the characteristics of flowing or pooled water at the bottom of the snowpack.

Watching snow melt in the Arctic has been compared by some to being as exciting as watching paint dry, but it is far more exciting and dynamic than that. Initially, changes happen slowly while the snow cover remains above 80%, but then reductions in the albedo of the landscape, from about 0.8 to 0.4, combined with rising spring temperatures, begin to accelerate the melt. It happens so quickly that no matter how hard the field team works, they cannot keep up with documenting the changes. At first, liquid water is scarce—only a few wet layers of snow in the snowpack. But then, water becomes ubiquitous, transporting melt energy and creating an extremely heterogeneous albedo and melt landscape. At the end of each field season, the SALVO team is exhausted, relieved to see the snow gone, and joyful to play in the melt ponds on the sea ice under the midnight sun.

Overall, the 2024 SALVO field campaign was a highlight, reflecting numerous lessons learned from 2019 and 2022. Daily measurements were taken more than ten times at each site, resulting in a comprehensive time series of snow conditions and albedo. The team deployed using snowmachines and then on foot when snowmachine travel was no longer permitted on the melting tundra. Instrument mounts and packaging were optimized for quick deployment, regardless of the mode of transportation.

SALVO Project Field Participants

Note: Collaborator means funded by external projects.

2024 Field Season

- University of Alaska Fairbanks: Jennifer Delamere (PI), Matthew Sturm (Co-I), David Clemens-Sewall (research scientist), Marc Oggier (research scientist), Serina Wesen (science educator, collaborator), Phillip Wilson (research technician, collaborator)
- NOAA: David Clemens-Sewall (research scientist, collaborator)
- University of Washington: Melinda Webster (Co-I), Zac Espinosa (graduate student, collaborator), David Shean (research scientist, collaborator), Steve Warren (research scientist, collaborator)

2022 Field Season

- University of Alaska Fairbanks: Jennifer Delamere (PI), Matthew Sturm (Co-I), Melinda Webster (Co-I), Hannah Chapman-Dutton (graduate student), Owen Larson (research technician), Ema Mayo (research technician), Anika Pinzner (graduate student), Phillip Wilson (research technician), Serina Wesen (science educator, collaborator)
- Dartmouth College: David Clemens-Sewall (graduate student, collaborator)
- University of Washington: David Shean (research scientist, collaborator)

2019 Field Season

- University of Alaska Fairbanks: Matthew Sturm (PI), Jennifer Delamere (Co-I), Trevor Grams (research technician), Anika Pinzner (graduate student), Ema Mayo (research technician), Phillip Wilson (research technician)
- Dartmouth College: Don Perovich (Co-I)

2.0 Results

2.1 SALVO Measurements

The SALVO I and II field campaigns took place over three consecutive field seasons at the North Slope of Alaska Atmospheric Observatory: 2019, 2022, and 2024. Each season unfolded in two stages: April (pre-melt) and May-June (sustained melt). Measurements of snow depth and characteristics, albedo (both all-wave and spectral), and energy balance were collected along three 200-meter lines (ARM, BEO, and ICE) on a near-daily basis. Additionally, snow depth was recorded along kilometer-long lines adjacent to the three sites in 2024. Combined with ground measurements, aerial photography was captured over the 200-meter and longer lines. These images were then processed to create ortho-photo maps, allowing for the computation of snow-covered and snow-free fractions of the landscape. The overall goal of these measurements was to compile a coordinated set of images, albedo readings, and snow depths and qualities to explore how the landscape's albedo evolves in spring as snow melts, varying by spatial scale. To aid in this scaling exploration, we also requested imagery from Maxar WorldView in 2024 surrounding our key measurement zones.

2.2 SALVO Campaign Daily Measurement Rotations

The field campaign was based at the ARM NSA Duplex. Most field participants were lodging in the duplex, and group meals were cooked there. Transport to the field sites (two on tundra, one to two on sea ice) was by snowmobile, occasionally by truck (to BEO and ARM sites; the ICE site on Elson Lagoon was only accessible by snowmobile). Each field day (weather permitting) began with a group breakfast, then the field team (2 to 7 people, depending on the day and tasks needed) would venture out to the sites. Plastic sleds were set up so instruments and gear could be readily loaded and unloaded at the sites. Tasks at each site included:

1. Stretch out 100-meter tapes along the 200-meter lines.
2. Use a GPS-enabled snow depth probe to measure snow depth along the lines.
3. An ASD FieldSpec4 Field Spectrometer was used to measure the spectral albedo at 41 locations along the 200-meter line.
4. Set up a fixed Kipp and Zonen albedometer to monitor the solar radiation during the measurement period [2024].
5. Use a Kipp & Zonen albedometer (one upward and one downward-looking all-wave radiometer) to measure the all-wave albedo at 41 locations along the line (every 5 meters) [2024, 2022-limited].
6. Use a corer to take snow samples for density and snow-water equivalent measurements.
7. Take photographs of the footprint of each albedo measurement along the 200-meter lines.
8. Dig a snow pit to examine the snow characteristics, particularly the location and amount of liquid meltwater in and below the snow.

During SALVO I, we identified specific, consistent snow melt-out patterns. Based on this recognition, we also began to measure what we called “library sites” in 2022 (limited) and 2024. At these sites, which measured approximately 5 by 20 meters, we conducted all the same types of measurements listed above but with much tighter spacing. We also repeated albedo measurements at these sites using the Kipp and Zonen albedometer and spectral field spectrometer. These were designed to assess the repeatability of the albedo measurements, the extent to which slight off-level measurements deviated from fully-level ones, and how slight changes in sky conditions over just a few minutes affected the albedo.

In 2024, we conducted an additional field activity focusing on the “long lines” adjacent to our main sites, which extended much further. Along these long lines, we used a GPS-enabled snow depth device to perform repeated (time series) snow depth measurements. We also installed mini data loggers to record air temperatures and snow-ground interface temperatures. The latter serves as crucial diagnostics for water accumulation at the base of the snow, an essential process that occurs about midway through the spring melt.

2.3 Field Logistics Itemized

- Facilities & Land Utilized
  - ARM NSA C1: Great White, Guest Instrument Facility, and tundra south of the facility
  - Barrow Environmental Observatory, including ARM NSA E12

  - ARM NSA Maintenance Shed
  - ARM NSA Duplex
  - ARM Laboratory at Barrow Arctic Research Facility
  - UIC Building 553 Sturm Storage Area and Large Garage for sled loading/unloading (external support for space)
- Team lodging
  - NSA Duplex
  - UIC Scientific Lodging (ASR DE-SC0019107 and external support)
- Transportation
  - Truck Rental/UIC Science (ASR DE-SC0019107)
  - Snowmachines pulling sleds
    - ARM NSA onsite machines (2)
    - Sturm-owned machines (2)
    - UIC Science Support (+2 machines)
  - 2024: NSA ARM Financial Support
  - 2019, 2022: ASR DE-SC0019107 Financial Support
    - By foot, pulling sleds when snowmachine travel was no longer permitted across the melting tundra
- Field Safety Training
  - Example for 2024: PI Delamere prepared a field safety plan at the University of Alaska Fairbanks. This safety plan was signed by all participants and provided to the ARM program.
  - A polar bear safety course was taught specifically for the SALVO team by Arctic Wild (https://arcticwild.com/) Owner and Instructor Michael Wald. This training was recorded and can be provided upon request.
  - A shotgun safety course was provided by the University of Alaska Fairbanks (ASR DE-SC0019107).
  - Onsite by the ARM NSA Staff
  - Onsite by the UIC Science Support Staff
- 2024 Permit Example
  - NSB/BRW 24-524, Administrative Approval, Snow Albedo Evolution (SALVO 2024)
    - Required testimony by PI Delamere at a North Slope Borough planning meeting in Winter 2024
    - This permitting paperwork can be provided upon request to PI Delamere.
  - Land Access permits provided by ARM (5) or by purchase via our ASR award: https://uicalaska.com/our-lands/land-access/

2.4 Results

Although fieldwork for SALVO is complete, science analyses continue under ASR funding. Based on three years of fieldwork, we have identified salient features of snowmelt on tundra and sea ice during the melt:

1. It is always diachronous (e.g., occurring at different times and rates across a landscape that may seem uniform to the eye). Snowmelt at SALVO exhibited several distinct phases, and we are articulating these based on SALVO observations and published literature.
2. Lateral advection of subnivean meltwater and possibly warm air from bare patches adds to the complexity of the melt. This advective heat leads to sea ice and tundra pond and puddle formation. These water features have extremely low (<0.1) albedos that feed into additional melting.
3. At least seven meltwater-related mechanisms enhance (in some locations) or retard (in other locations) the rate of melt-out and contribute to the date of complete melt-out.
4. While the snow cover's albedo decreases by about 20% early in the snowmelt, the most significant decrease (from 0.65 to 0.16) occurs in just a few days; this abrupt reduction is also diachronous.
5. While it is reasonable and potentially accurate to use areal averages of albedo for modeling atmospheric processes, these averages do not adequately describe the mechanisms of albedo and energy exchange at snow, tundra, and ice surfaces. SALVO aims to enhance future albedo characterizations used in models that support weather forecasting, human trafficability, and hydrology assessments.

2.4.1 Maps, Photos, Figures

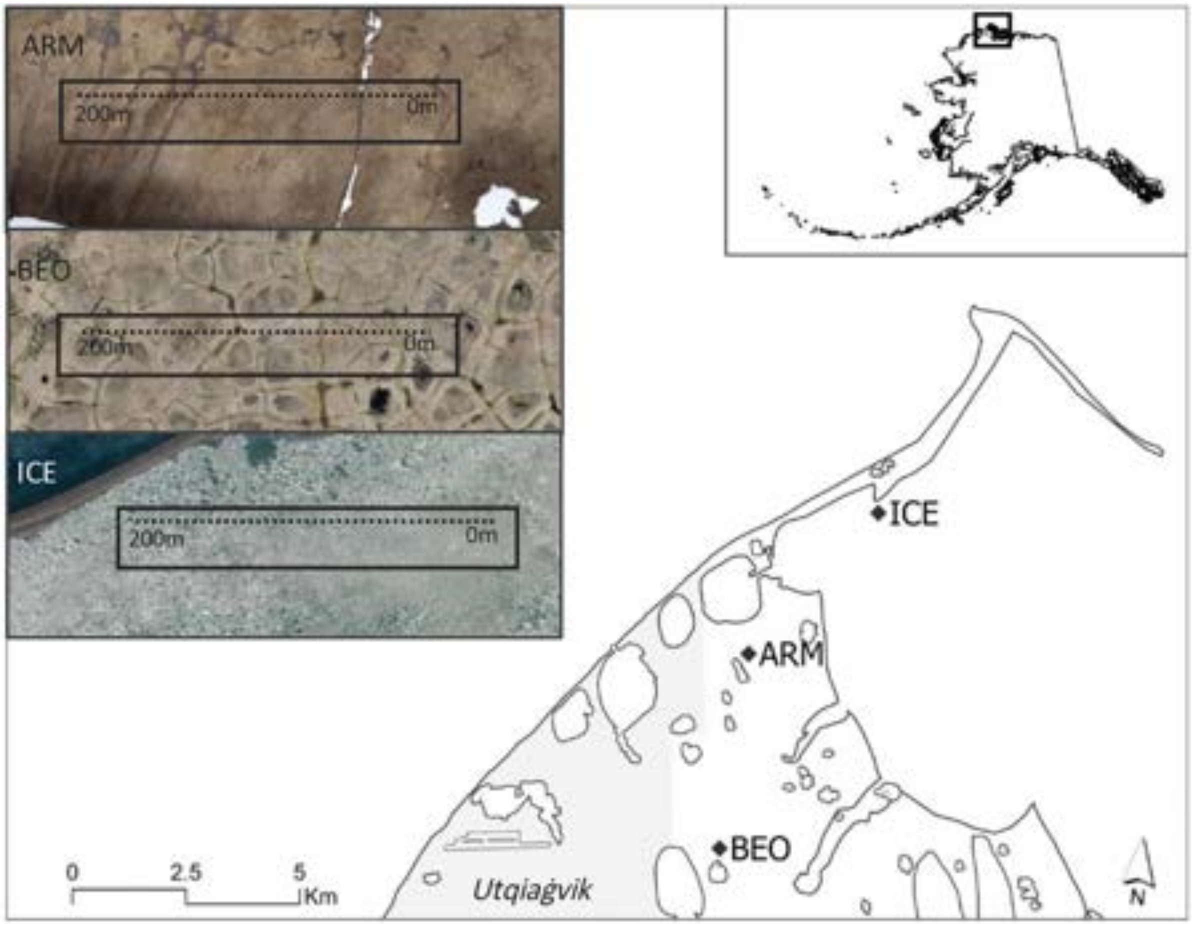

Figure 1. The three locations where we monitored snow melt near Utqiaġvik, AK: ARM, BEO, and ICE. The measurement swaths (outlined in black) are 20 by 200 m; along the northern edge of each swath, we measured snow depth at 1-meter and albedo at 5-meter intervals (dotted lines). From Pinzer et al. (2024) publication.

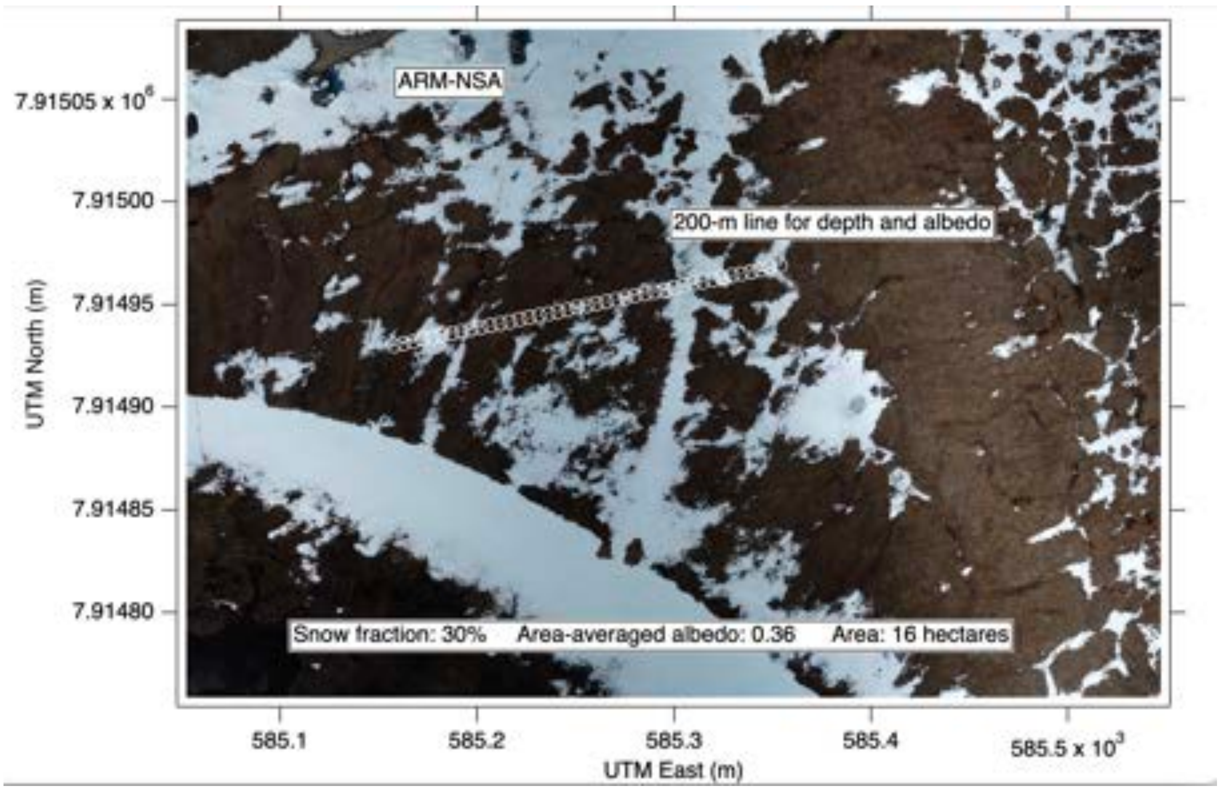

Figure 2. The 200-meter line at the ARM-NSA site. The color image is an ortho-rectified composite from aerial photography. The chain of white circles delineates the 200-meter measurement line and the 41-locations where albedo was measured. For reference, the snow areas have an albedo of about 0.8, while the tundra areas have an albedo of 0.16.

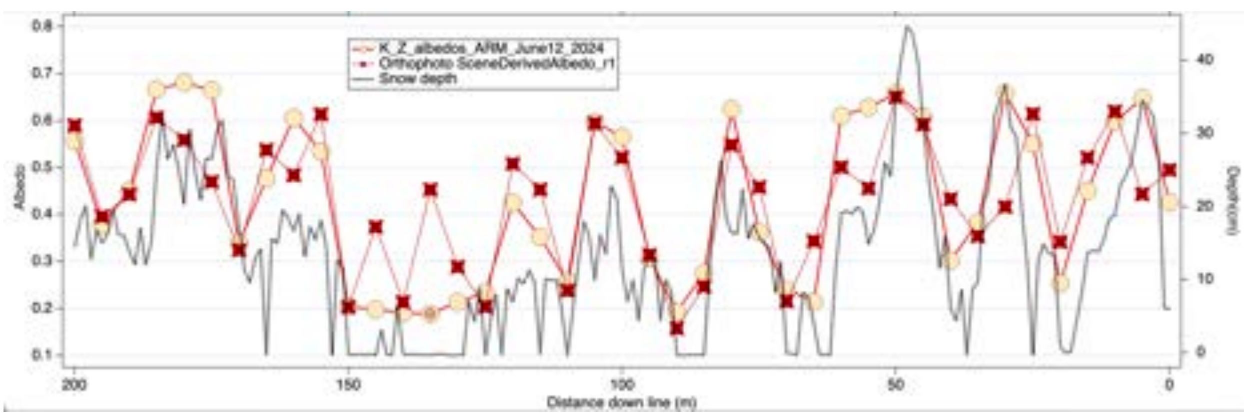

Figure 3. Radiometer-measured (tan) and computed-from-photo (red) albedos for the 41 locations shown in Figure 1. The black dashed line is the snow depth. Same date as above.

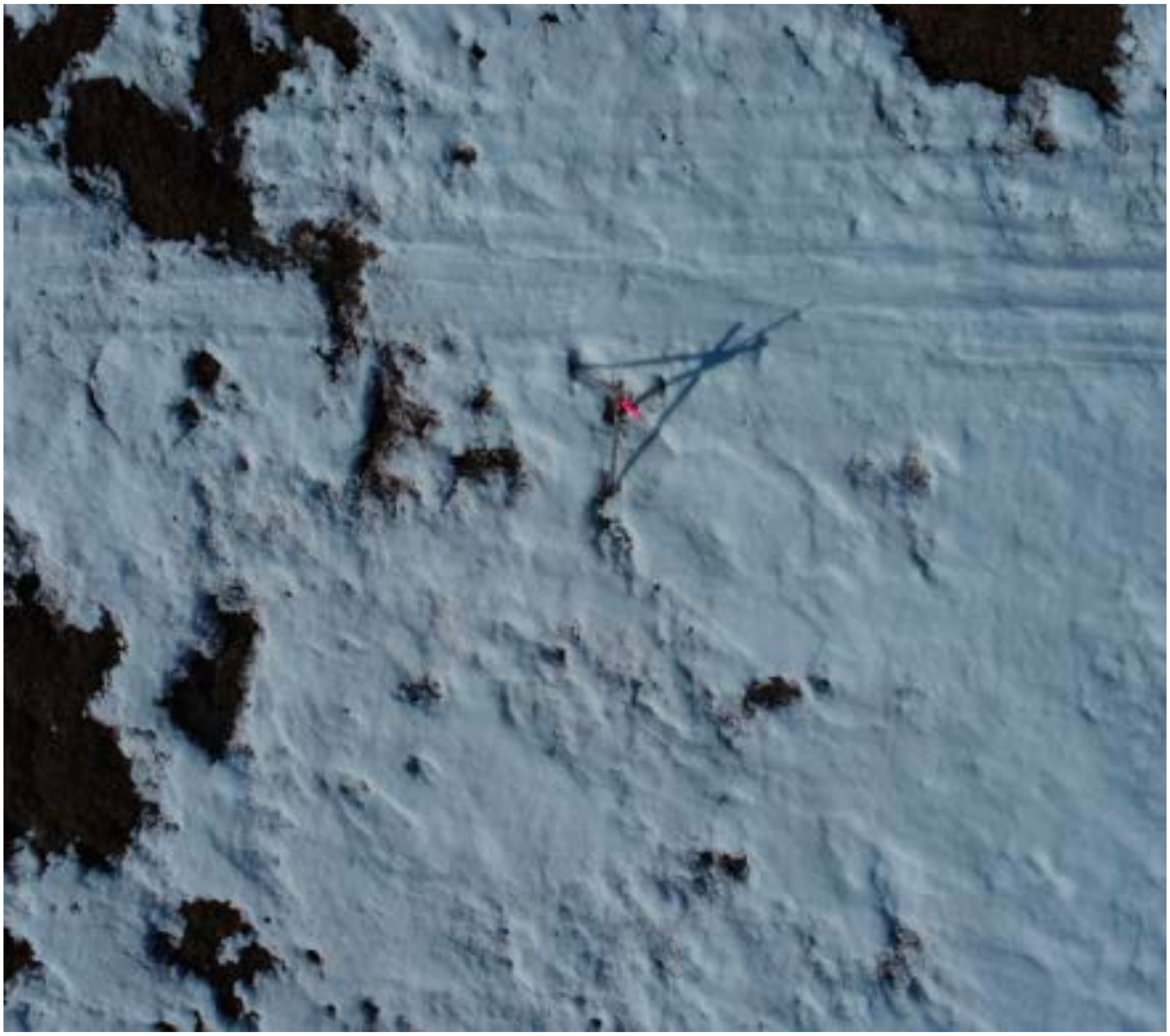

Figure 4. A nadir image of the footprint of the ASD and Kipp and Zonen albedometers. The orange flag is on a small tripod about 1-meter across. The albedometer footprints are about 2-meter in diameter and 1.5-meter south (below) the tripod, which is at the 100-meter midpoint of the 200-meter line shown in Figure 2.

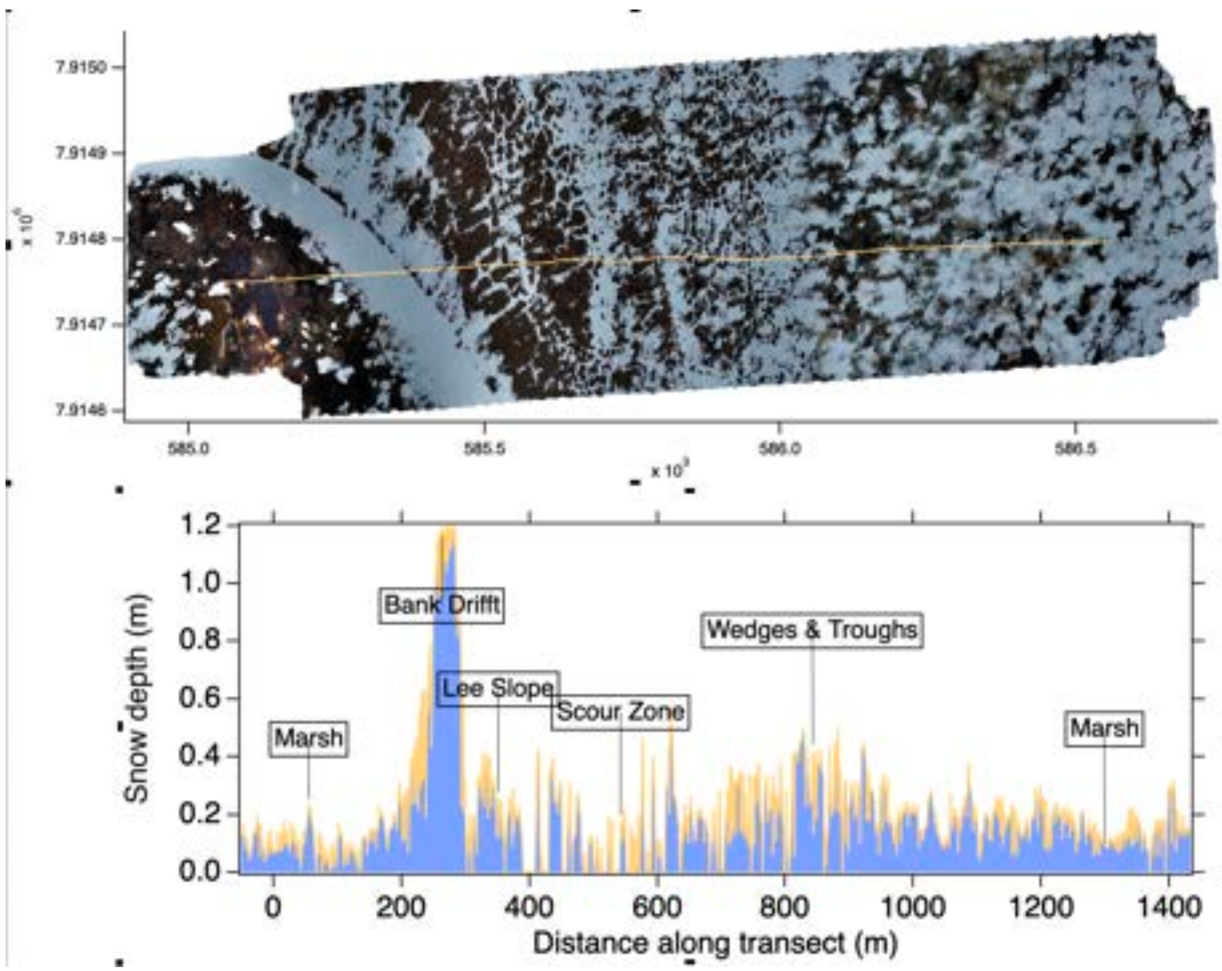

Figure 5. An example of one of the SALVO long lines (ARM). The snow depth (blue fill) along the gold line in the orthomosaic passes through 5 distinct terrain zones, each with different areal values of albedo at this stage of melt, hence a different surface energy balance. Heat (in the form of heated water and air movement) couples the zones together but in complex ways.

Figure 6. NSA E12 caribou grazing (2024). Credit: Jen Delamere.

Figure 7. Snowflakes up close (2024). Credit: Jen Delamere.

Figure 8. The SALVO team deploys to the field from NARL Building 553 (2024). Photo Credit: SALVO Team.

Figure 9. Measuring snow water equivalent on Elson Lagoon (L to R: Jen Delamere, Phillip Wilson) (2024). Photo: Zac Espinosa.

Figure 10. Photographing snow pit (Front: David Clemens-Sewall, Back: Melinda Webster) (2024). Credit: Jen Delamere.

Figure 11. Studying snow stratigraphy at NSA E12 (L to R: Phillip Wilson, Jen Delamere, Matthew Sturm, David Clemens-Sewall) (2024). Credit: Marc Oggier.

3.0 Publications and References

- Websites
  - ARM (SALVO I): https://www.arm.gov/research/campaigns/nsa2019salvo
  - ARM (SALVO II): https://www.arm.gov/research/campaigns/nsa2022salvoii
- Blogs in ARM News
  - David Clemens-Sewall, 2024: https://www.arm.gov/news/blog/post/101288
  - Zac Espinosa, 2024: https://armgov.stg.arm.gov/news/blog/post/100459
  - The Big Work of Small Campaigns, 2024: https://www.arm.gov/news/features/post/99696
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  - 2021 UEC Profile, Delamere: https://www.arm.gov/news/features/post/73292
  - 2020 Sturm Profile: https://asr.science.energy.gov/news/program-news/post/13183
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  - Pinzner A, M Sturm, J Delamere, and A Mahoney. 2024. "An Examination of Water-Related Melt Processes in Arctic Snow on Tundra and Sea-Ice." 60(1), 10.1029/2022WR033440.
- Conference presentations with lead author listed
  - Public Outreach Talk at the Geophysical Institute 2025: Onset and Evolution of Snow Melt in Utqiagvik, AK 2024 (Clemens-Sewall)
  - Arctic Marine Science Symposium 2025: Chasing the melt: Timing of snowmelt between tundra and sea ice near Elson Lagoon, Utqiagvik, AK (Oggier)
  - American Geophysical Union 2024: How Snow Drives the Springtime Evolution of Surface Albedos in the Arctic Coastal Environment (Delamere)

- American Geophysical Union 2023: An Examination of Water-Related Melt Processes in Arctic Tundra and Sea-Ice Snow (Pinzner)
- American Geophysical Union 2020: Spatial Evolution of Snow Melt On the Arctic Coast: A Field Campaign in Utqiaġvik, Alaska (Pinzner)
- ARM/ASR Joint Meeting 2023: Snow Melt Mechanisms and Outcomes at ARM-NSA Observed During SALVO (Sturm)
- ARM/ASR Joint Meeting 2022: A Long-time Coming: The Utqiagvik Snowmelt of 2022 (Delamere)
- ARM/ASR Joint Meeting 2021: The Ground Effect: Snow, Ice, and Tundra Albedo in the Arctic (Pinzner),
- ARM/ASR Joint Meeting 2020: Snow Melt Trajectories and the Evolution of Surface Albedo at Utqiagvik, Alaska (Sturm)

Note: Work on data analyses under the SALVO team's ASR award will continue through August 2025.

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