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Measurement of Terrestrial Snow

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LAST MODIFIED: 24 FEBRUARY 2021
DOI: 10.1093/OBO/9780199874002-0225

Introduction

Snow on the land surface is an important component of the hydrological cycle in cold regions and acts as a hydrologic reservoir with a residence time that introduces a delay before ablation when runoff from snowmelt enters rivers, streams, and aquifers. Mass and energy fluxes between the snowpack and the atmosphere affect climate, temperature, and biogeochemical cycles in cold regions. Snow is a thermal insulator and the presence or absence of snow influences soil temperatures and soil water content that affect the growth of plants and agricultural crops. Snowpack chemistry is indicative of atmospheric pollutants and ions present in snowmelt runoff affect water quality and biological processes. Changes in the snowpack due to mass and energy fluxes associated with heat transport modify snow particle size, snow structure, and density, influencing albedo, permeability, air and water transport through snow, the rate of snowmelt, and mechanical properties. In some regions, snowmelt is a source of water for hydroelectric power generation, agricultural production, and human consumption. Accumulation of snow in complex terrain and snowpack metamorphic processes contribute to avalanche activity that redistributes snow between different areas but also influences biogeography and creates human hazards in regions where the spatial distribution of snow is important for winter recreation and skiing activities. Wind is also responsible for redistribution of snow and affects the spatial distribution of snowcover. Measurement of snow quantifies the spatial distribution of snowpack properties and provides inputs for mathematical models used for prediction and forecasting of flooding, drought, runoff, climate change, and avalanche activity for assessment of water resources and regional hazards. Snowpack measurements also provide insight into hydrological processes related to snow in a temporal and geographic context, allowing for a better scientific understanding of these processes and providing a means for the development of more accurate mathematical models. This bibliography provides an overview of how terrestrial snow properties and processes are measured. Papers were selected for this bibliography based on pedagogical value and an emphasis on important research conducted during the last thirty years for an up-to-date overview, although earlier papers and monographs are also included that had an influence on snow hydrology in a historical context.

General Introductions and Reference Works

The Gray and Male 1981 handbook serves as a basic starting point for the science and associated engineering related to snow and snowpack processes. DeWalle and Rango 2008 provides an updated overview compared to Gray and Male 1981 but does not include the same level of information related to civil engineering applications. The Armstrong and Brun 2010 book has more of a focus on snow-climate interactions, whereas Jones, et al. 2011 clearly shows relationships between biogeography and snowpack processes. Seidel and Martinec 2004 has a primary emphasis on remote sensing whereas DeWalle and Rango 2008 covers remote sensing of snow for model assimilation where the remote sensing data is utilized for model inputs. Blöschl 1999 provides an overview of how scale affects the measurement and associated spatial analysis of snow.

Armstrong, R. L., and E. Brun, eds. *Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling*. Cambridge, UK: Cambridge University Press, 2010.

This monograph features individual chapters written by researchers who have extensively conducted studies related to snowpack modeling, energy, and mass balances. Chapters on measurement of snow and snow physics make this book an excellent introduction to snow with a regional and global emphasis on spatially distributed climate and atmospheric processes.

Blöschl, G. “Scaling Issues in Snow Hydrology.” *Hydrological Processes* 13.14–15 (1999): 2149–2175.

A wide-ranging paper that reviews the variability of spatial snow datasets, indicating methods for characterization as well as spatial upscaling and downscaling. The geostatistical variogram is clearly explained as a starting point for characterizing how a snowpack quantity changes over distance. Fractal scaling is also addressed in the context of variogram analysis. The author introduces frameworks for quantifying scale, indicating how artifacts can influence quantitative calculations.

DeWalle, D. R., and A. Rango. *Principles of Snow Hydrology*. Cambridge, UK: Cambridge University Press, 2008.

A wide-ranging textbook that describes basic principles of remote sensing and snowpack modeling for estimation of accumulation, snowmelt, and runoff. Suitable for use in a class at the undergraduate level.

Gray, D. M., and D. H. Male, eds. *Handbook of Snow: Principles, Processes, Management and Use*. Toronto: Pergamon Press Canada, 1981.

Well-known to snow scientists, consultants, and resource managers as a classic handbook, this work does not include recent advances in measurement and modeling of snow but serves as an important reference on snowpack properties and physics. Chapters on measurement, snow surveying, avalanches, and civil engineering applications make this handbook suitable for classes at the graduate level or as a general reference work.

Jones, H. G., J. W. Pomeroy, D. A. Walker, and R. W. Hoham, eds. *Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems*. Cambridge, UK: Cambridge University Press, 2011.

Discusses the physics of snowpack processes in the context of plant and animal biogeography. Provides excellent overviews of the spatial distribution of plants related to snow-vegetation interactions but also discusses snow microbiology and animals that live in the snowpack. A chapter on tree-ring dating for measurement of climate associated with past snowcover enhances the wide range of topics in this monograph.

Seidel, K., and J. Martinec. *Remote Sensing in Snow Hydrology: Runoff Modelling, Effect of Climate Change*. Berlin and London: Springer Science & Business Media, 2004.

Shows how remote sensing can be used to provide inputs to mathematical models used for prediction of future and present climate processes. This book provides an excellent description of statistics used for characterization of snow-covered area and implications for runoff.

Journals

The journals listed in this section publish papers that are explicitly related to snow, snowpack processes, and associated spatial analyses in cold environments. Other environmental and remote sensing journals are listed throughout the bibliography. *Proceedings of the Eastern Snow Conference* and *Proceedings of the Western Snow Conference* are good starting points for students and researchers who would like to understand current trends in snow science and the associated conferences provide excellent venues for connecting with influential scientists and professionals. *Proceedings of the International Snow Science Workshop* is the journal of a similar venue primarily intended for dissemination of avalanche research and associated civil engineering related to snow and snowpack processes in complex terrain. *Cold Regions Science and Technology* has a focus on engineering in cryospheric environments but also publishes scientific papers on measurement and spatial analysis. *Hydrological Processes* publishes studies on snow along with other research on the hydrologic cycle and often contains studies associated with papers published in the *Proceedings of the Eastern Snow Conference* and *Proceedings of the Western Snow Conference*. *The Cryosphere* is a well-known open access journal that contains snow studies related to climate and meteorological phenomena. *Water Resources Research* publishes papers related to snow hydrology and the research focus is often related to snowpack assessment for natural resources management. *Journal of Glaciology* and *Annals of Glaciology* once served as venues for publication of snow science research in the early 20th century but the current emphasis of these journals is on glaciers or the Greenland and Antarctic ice sheets and associated snow processes. *Arctic, Antarctic, and Alpine Research* is a holistic journal that provides studies on snow and spatial processes with an emphasis on environmental and biological systems in cold regions.

***Annals of Glaciology*. 1980–.**

Similar to the *Journal of Glaciology*, this publication contains papers that were foundational for the study of cryospheric environments from the 1980s onward. Issues of this journal are thematic: authors submit manuscripts based on a call for papers related to a set publication schedule associated with specific International Glaciology Society (IGS) symposia. Papers on snow in relation to cryospheric processes are accepted. This includes permafrost along with research conducted on glaciers.

***Arctic, Antarctic, and Alpine Research*. 1969–.**

Publishes papers that provide a synthesis related to environmental systems that operate in cold environments at high latitudes and elevations. The emphasis of this journal is on interdisciplinary research related to biology and hydrology. Papers have also been published by this journal on human geography and sociology in relation to snow and snowpack processes.

***Cold Regions Science and Technology*. 1979–.**

A mixture of scientific and engineering studies related to snow are found in this journal that also includes important papers related to research in cold environments of the Arctic, Antarctic, and Greenland. The journal is a useful source of research on the mechanical properties of snow in relation to spatial processes governing avalanches, snowpack evolution, snow redistribution in complex terrain, and civil engineering in cryospheric environments.

***The Cryosphere*. 2007–.**

An open-access journal with online peer-review and publication, articles published in this journal are placed under a Creative Commons license that permits papers to be freely shared. The focus of the journal is on measurement, modeling, and the characterization of hydrological processes related to snow and ice in cold regions. Many papers published in this journal show linkages between cold regions and planetary climate systems.

***Hydrological Processes*. 1986–.**

This journal publishes papers related to all aspects of the hydrological cycle including snowpack processes, modeling, and spatial analysis. Also includes papers related to sub-surface hydrology in relation to snowmelt, infiltration, and snowpack evolution.

***Journal of Glaciology*. 1947–.**

In the mid-20th century, this journal published many of the original papers that provided a scientific basis for the study of ice sheets, glaciers, and cryospheric processes. Early snow surveying research was also published by this journal. Papers on snow and snowpack processes are currently accepted by this journal but these are mostly related to snow accumulation in relation to glaciers and ice sheets.

***Proceedings of the Eastern Snow Conference*.**

Papers published in the proceedings of this conference tend to have a focus on research conducted by investigators in eastern North America. Since the conference acts as a convening location for snow scientists in this geographical location, attendance is useful and recommended for students, researchers, and practitioners in this region who study hydrological processes. The papers published in the proceedings have not been rigorously peer-reviewed, but are still considered by snow measurement practitioners to be an important source of useful information on techniques and practices related to snow measurement and are cited in the hydrological literature. Some conference papers are later re-published in other journals.

***Proceedings of the International Snow Science Workshop*.**

An annual workshop that brings together researchers, consultants, and resource managers who study and manage snow and snowpack processes. The focus of this workshop is mostly on avalanches and snowpack processes in Alpine regions, although some papers have been published in the proceedings related to cryospheric environments, ski operations, and civil engineering structures for snow management.

***Proceedings of the Western Snow Conference*.**

Analogous to the Proceedings of the Eastern Snow Conference but the geographic focus is on snow, snowpack processes, and management in the western United States and Canada. This includes publications related to snow and snow surveying in the Rocky Mountains and mountain ranges of California. Conference attendance is highly encouraged for those who study and manage snow in this region. Analogous to the Proceedings of the Eastern Snow Conference, the papers have not been rigorously peer-reviewed but are cited in the hydrological literature.

***Water Resources Research*. 1965–.**

This journal publishes papers related to the measurement and areal characterization of snow along with research related to water quality, runoff, and sub-surface processes. Remote sensing of snow and snow measurement instrumentation are two important areas of interest for this journal.

Measurement

Snow measurement techniques and instrumentation allow scientists to obtain data for spatial analyses as well as model application and verification. Overviews provide an understanding of the different methods for obtaining data and are useful for pedagogical and teaching purposes. Depth and Stratigraphy methods quantify spatial patterns of snow accumulation and metamorphic processes where the physical properties of the snowpack progressively change due to time, mass, and energy fluxes. Density methods provide estimates of a bulk physical property that is multiplied by snow depth to compute Snow Water Equivalent (SWE) as a numerical value that represents the resulting depth of water at a geographic location. Methods also exist for determination of SWE without depth or density measurements. Liquid Water Content (LWC) and associated measurements quantify snowpack wetness for characterization of metamorphic processes. LWC affects snow particle size, the temporal albedo of the snowpack associated with changes in snow particle size, and meltwater fluxes that influence the rate, magnitude, and timing of snowmelt. Snow Microstructure measurements are representative of snowpack metamorphism that governs the propagation of heat, gas, air, water, and chemical transport through the porous snowpack. Snow-Covered Area (SCA) represents the amount of snow accumulated on the land surface. The spatial distribution of SCA is related to accumulation, blowing snow, and heat transport processes that result in snowcover variability influencing the time and magnitude of ablation and runoff. Blowing Snow is responsible for snow redistribution, sublimation during wind transport, and mechanical disaggregation of snow particles during transport. The presence of blowing snow in cold regions also reduces visibility and thereby creates human hazards for travel in cold regions. Measurements of Temperature and Thermal Properties quantify heat transport through the snowpack that influences metamorphism and snowmelt. Optical Properties are utilized for remote sensing of snowpack properties and provide insight into energy and mass exchanges at the snow surface and within the snowpack. Measurement of snowpack Chemical Properties and Permeability quantify water quality associated with snowmelt runoff as well as biogeochemical cycles, gas transport between soils, and the snowpack and atmospheric chemistry including the transport of pollutants and particulate matter. Mechanical Properties of snow are associated with slope stability and are quantified by measurements to understand the rate and timing of avalanche processes that serve as a means of snow redistribution but also cause human hazards in complex terrain.

Overviews

Church 1933 provides historical context on early-20th-century snow surveying and interpretation of snowpack conditions. Fierz, et al. 2009 describes a framework for description and scientific reporting of snowpack measurements and can be considered as a document that provides the most recent guidelines for research and operational use. Although an older publication, Goodison, et al. 1981 is still an excellent starting point for students and researchers who require a concise overview of how to collect and analyze data, whereas Goodison, et al. 1987 also provides historical context for snow surveying in the 20th century. Rasmussen, et al. 2012 reviews common snow measurement gauges. Kinar and Pomeroy 2015 provides an overview of devices for measurement of snow and snowpack processes, whereas Pirazzini, et al. 2018 shows how snow measurement devices can be used in an operational context. Schweizer, et al. 2003 is an overview of data collection procedures for avalanche forecasting and provides a detailed overview of avalanche physics. Consult Frei, et al. 2012 for selection of remote sensing data products related to snow.

Church, J. E. "Snow Surveying: Its Principles and Possibilities." ***Geographical Review*** **23.4 (1933): 529–563.**

This paper provides an important historical context for the first snow surveying measurements made in the western United States. Differences in sampling location, field site selection, hydrological processes, and associated areal averaging of Snow Water Equivalent (SWE) measurements are also discussed. Church was responsible for popularizing snow surveying techniques in the early 20th century.

Fierz, C., R. L. Armstrong, Y. Durand, et al. ***The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology N°83, IACS Contribution N°1, UNESCO-IHP, Paris*****. Paris: UNESCO, 2009.**

This report provides a standardized system for classifying and measuring snow using snowpits. Reporting and identification methods related to layers in the snowpack (snowpack stratigraphy) and the crystallography of snow particles in each layer is provided. The report offers a theoretical framework that is useful for all snowpit observations.

Frei, A., M. Tedesco, S. Lee, et al. "A Review of Global Satellite-Derived Snow Products." ***Advances in Space Research*** **50.8 (2012): 1007–1029.**

A wide-ranging review of raster snowpack data products that are derived from satellite remote sensing. The review is structured based on satellite sensors and technology. Dataset intercomparisons are also presented by the authors of this paper.

Goodison, B. E., H. L. Ferguson, and G. A. McKay. "Measurement and Data Analysis." In ***Handbook of Snow: Principles, Processes, Management and Use*****. Edited by D. M. Gray and D. H. Male, 191–274. Toronto: Pergamon Press Canada, 1981.**

Discusses the creation of snowpits and transects for measurement of snow. An overview of snow measurement instrumentation, data reporting, and post-processing is also provided. Although dated, this chapter has been extensively used by snow measurement schools and in classrooms to train snow scientists.

Goodison, B. E., J. E. Glynn, K. D. Harvey, and J. E. Slater. "Snow Surveying in Canada: A Perspective." ***Canadian Water Resources Journal*** **12.2 (1987): 27–42.**

Although this paper has a Canadian regional context, the authors describe the establishment of snow courses to obtain areal estimates of SWE. Snow sampling techniques are discussed, including the use of satellite remote sensing. The paper serves as an important historical overview of snow sampling in the latter part of the 20th century.

Kinar, N. J., and J. W. Pomeroy. "Measurement of the Physical Properties of the Snowpack." ***Reviews of Geophysics*** **53.2 (2015): 481–544.**

A wide-ranging overview that discusses the design and operation of devices for measurement of snow. The authors describe mechanical and electronic devices for physical properties of snow measurement and indicate directions for future instrumentation development.

Pirazzini, R., L. Leppänen, G. Picard, et al. "European In-Situ Snow Measurements: Practices and Purposes." *Sensors* 18.7 (2018): 2016.

This paper serves as a more recent complement to the Goodison, et al. 1987 paper and describes ground-based snowpack measurement by researchers at sites situated in Europe. The paper is novel since the authors quantify measurement purpose and instrumentation type at numerous field site locations. Descriptive statistics including pie charts indicate the practical use of instrumentation and this paper is therefore a companion to the Kinar and Pomeroy 2015 publication.

Rasmussen, R., B. Baker, J. Kochendorfer, et al. "How Well Are We Measuring Snow: The NOAA/FAA/NCAR Winter Precipitation Test Bed." *Bulletin of the American Meteorological Society* 93.6 (2012): 811–829.

The authors describe cosmic-ray and GPS measurements of snow in an operational context. This paper serves as a good overview suitable for use in hydrometeorology classes at the undergraduate or graduate level.

Schweizer, J., J. B. Jamieson, and M. Schneebeli. "Snow Avalanche Formation." *Reviews of Geophysics* 41.4 (2003): 1016.

This widely cited paper reviews the physics of avalanche activity in an environmental and spatial context, identifying factors such as temperature, mechanical properties of snow, and snow structure as related to the failure and collapse of snowpack layers. Relationships are identified between spatial variability and avalanche activity.

Depth and Stratigraphy

The Intercomparisons section lists studies that analyze differences between measurement techniques for determination of snow depth. Depth Rods and Rulers are stationary or portable devices used to determine point measurements of snow depth or the distance of snowpack layers in a snowpit from the ground surface. Ultrasonic and Acoustic devices and methods measure snow depth using air-coupled pressure waves. Airborne LIDAR refers to devices mounted on near-surface remote sensing platforms that use pulsed lasers to determine distance to the snow surface, Terrestrial Laser Scanning (TLS) utilizes lasers situated on or near the ground surface. Radar devices use electromagnetic waves to determine snow depth and stratigraphy. UAVs and Near-Surface Remote Sensing techniques measure snow depth using Structure-from-Motion (SfM) algorithms and cameras mounted on small near-surface aircraft. GPS measurement of snow depth is accomplished by utilizing signals from GPS satellites.

Intercomparisons

Prokop, et al. 2008 compares ground-based terrestrial LIDAR devices to manual observations.

Prokop, A., M. Schirmer, M. Rub, M. Lehning, and M. Stocker. "A Comparison of Measurement Methods: Terrestrial Laser Scanning, Tachymetry and Snow Probing for the Determination of the Spatial Snow-Depth Distribution on Slopes." *Annals of Glaciology* 49 (2008): 210–216.

This paper demonstrates the differences between snow depth observations made using LIDAR (Light Detection and Ranging), total surveying stations, and ultrasonic depth sensor measurements. The methods are clearly described along with a viable post-processing flow that can be used for other studies. Areal LIDAR scans are compared for reproducibility.

Depth Rods and Rulers

Henderson 1953 and Miller 1962 provide schematic diagrams and operational deployment techniques of stationary snow-depth markers for measurement of snow depth. Woo 1997 indicates how depth rods can be designed. An automated device for fast and accurate depth measurements is described by Sturm and Holmgren 2018. Karpilo 2009 is an essential reference for measurement of snow depth and ablation on glaciers.

Henderson, T. J. “The Use of Aerial Photographs of Snow Depth Markers in Water Supply Forecasting.” *Proceedings of the Western Snow Conference* 21 (1953): 44–47.

A paper of historical interest that describes the use of stationary measurement rulers to measure snow depth in the mountains of California. The rulers are large enough to allow for the ruler markings to be visible from an airplane without the need for ground-based observations.

Karpilo, R. D. “Glacier Monitoring Techniques.” In *Geological Monitoring*. Edited by Rob Young and Lisa Norby, 141–162. Boulder, CO: Geological Society of America, 2009.

Discusses the use of ablation stakes and measurements for monitoring changes in snow depth and surface height on glaciers.

Miller, R. W. “Aerial Snow Depth Marker Configuration and Installation Considerations.” *Proceedings of the Western Snow Conference* 30 (1962): 1–5.

This paper describes the design and deployment considerations associated with stationary measurement rulers installed in California. A complete mechanical diagram of the stationary ruler is provided.

Sturm, M., and J. Holmgren. “An Automatic Snow Depth Probe for Field Validation Campaigns.” *Water Resources Research* 54.11 (2018): 9695–9701.

Describes a snow depth probe (“magnaprobe”) with a sliding assembly that automatically logs snow depth along a transect in conjunction with concomitant GPS measurements of geographic location. A backpack carries a datalogger used to store measurements collected by the probe. The authors demonstrate how areal snow-depth maps can be easily created using this device. The paper provides a detailed quantitative discussion of time required for measurements.

Woo, M.-K. *A Guide for Ground Based Measurement of the Arctic Snow Cover*. Downsview, ON: Climate Research Branch, Meteorological Service of Canada, 1997.

A classic reference that discusses depth rod design and operational use for field campaigns in the context of environmental processes particular to Arctic regions. Kinar and Pomeroy 2015 (cited under Density: Acoustic) provides a summary of snow depth rod design discussed by this reference.

Ultrasonic and Acoustic

Ultrasonic devices situated above the snowpack that use time-of-flight measurements and simple kinematics to determine snow depth are described by Gubler 1981; Goodison, et al. 1984; Goodison, et al. 1988; and Earl, et al. 1985. All these devices require concomitant measurements of air temperature to determine the speed of sound in air. Metcalfe, et al. 1987 is a good reference for providing historical context related to the adoption of ultrasonic snow depth sensors for operational use. Anderson and Wirt 2008 and Ryan, et al. 2008 identify errors associated with ultrasonic measurement of snow depth. Ryan, et al. 2008 provides filtering and analysis time-series processing techniques for ultrasonic snow-depth sensors. Varhola, et al. 2010 provides information on the development of low-cost ultrasonic sensors for measurement of snow depth. A novel ultrasonic sensor device for determination of glacier ablation that does not require measurement of air temperature is described by Keeler and Brugger 2012, and the authors discuss its application for measurement of snow accumulation. Albert 2001 was the first to show that air-coupled sound waves produced over a seasonal snow cover can determine snow depth using an inverse geophysical model.

Albert, D. G. “Acoustic Waveform Inversion with Application to Seasonal Snow Covers.” *The Journal of the Acoustical Society of America* 109.1 (2001): 91–101.

The paper introduces forward and inverse models of sound wave propagation through snow, demonstrating inversion algorithms to determine snow depth. The source signal was an impulse propagating horizontally over the snowpack.

Anderson, J., and J. Wirt. “Ultrasonic Snow Depth Sensor Accuracy, Reliability and Performance.” *Proceedings of the Western Snow Conference* 76 (2008): 99–105.

The paper assesses ultrasonic sensor operation to determine snow depth at seventy-six SNOTEL sites used for measurement of snow at locations in the United States. Measurement difficulties including transducer malfunction, snow, and wind effects are also described.

Earl, W. M., G. R. Grey, H. Conway, and J. Abrahamson. “Remote Sensing of Snow Accumulation.” *Cold Regions Science and Technology* 11.2 (1985): 199–202.

Describes the modification of a Polaroid rangefinder module to determine snow depth. A complete schematic of the measurement circuit is provided, including digital logic to trigger measurements every hour.

Goodison, B. E., R. A. Metcalf, R. A. Wilson, and K. Jones. “The Canadian Automatic Snow Depth Sensor: A Performance Update.” *Proceedings of the Western Snow Conference* 56 (1988): 178–181.

A companion paper to the Goodison, et al. 1984 publication showing how time series of snow depth at Environment Canada hydrometeorological stations were obtained using an updated version of the ultrasonic sensor system. Comparisons are also presented with snow rulers.

Goodison, B., B. Wilson, K. Wu, and J. Metcalfe. “An Inexpensive Remote Snow-Depth Gauge: An Assessment.” *Proceedings of the Western Snow Conference* 52 (1984): 188–191.

Presents a block diagram of an ultrasonic ranging system that was initially used for automated snow-depth measurements in Canada. A Polaroid rangefinder module that was readily available at the time was integrated into the system. Signal attenuation during periods of heavy snowfall is discussed.

Gubler, H. “An Inexpensive Remote Snow-Depth Gauge Based on Ultrasonic Wave Reflection from the Snow Surface.” *Journal of Glaciology* 27 (1981): 157–163.

Provides a list of engineering requirements for an ultrasonic snow-depth sensor and a clear picture of installation at a field site in Switzerland featuring a miniature snow roof. The paper describes acoustic scattering and attenuation due to snow drift and possible ultrasonic pulse attenuation by low-density snow.

Keeler, L., and K. A. Brugger. “A Method for Recording Ice Ablation Using a Low-Cost Ultrasonic Rangefinder.” *Journal of Glaciology* 58.209 (2012): 565–568.

Describes the design and deployment of an ultrasonic rangefinder that utilizes two ultrasonic sensor assemblies: one facing a fixed target situated above a glacier surface and the other directly facing the glacier surface. The ultrasonic pulse travel time to the fixed target and the known fixed target distance is used to determine the speed of sound in air without air temperature measurements.

Metcalfe, R. A., R. A. Wilson, and B. E. Goodison. “The Use of Acoustic Ranging Devices as Snow Depth Sensors: An Assessment.” *Proceedings of the Eastern Snow Conference* 44 (1987): 203–207.

An overview that identifies the deployment of ultrasonic depth-ranging sensors in an operational context.

Ryan, W. A., N. J. Doesken, and S. R. Fassnacht. “Evaluation of Ultrasonic Snow Depth Sensors for U.S. Snow Measurements.” *Journal of Atmospheric and Oceanic Technology* 25.5 (2008): 667–684.

Comparisons between two commercial ultrasonic sensors are provided at nine field sites situated across the continental United States. Site setup and data filtering algorithms are provided along with comparisons associated with manual snow-depth measurements.

Varhola, A., J. Wawerla, M. Weiler, N. C. Coops, D. Bewley, and Y. Alila. “A New Low-Cost, Stand-Alone Sensor System for Snow Monitoring.” *Journal of Atmospheric and Oceanic Technology* 27.12 (2010): 1973–1978.

Describes the development and deployment of an inexpensive ultrasonic monitoring sensor used to measure snow depth as the height of snow at sites in British Columbia. The paper provides a mathematical correction for errors occurring due to sensor inclination. Data quality for time series measurements are also discussed.

Airborne LIDAR

Deems, et al. 2013 provides a comprehensive review on how LIDAR (light detection and ranging) devices measure the distance to the snow surface and this publication is useful for pedagogical purposes. Hopkinson, et al. 2004 addresses challenges associated with LIDAR measurements and forest canopies, whereas Hopkinson, et al. 2012 is an important case study that demonstrates how LIDAR can be used for areal measurements of snow water equivalent (SWE). Hedrick, et al. 2015 compares LIDAR measurements to gridded datasets of snow depth.

Deems, J. S., T. H. Painter, and D. C. Finnegan. “Lidar Measurement of Snow Depth: A Review.” *Journal of Glaciology* 59.215 (2013): 467–479.

An overview that is useful as a starting point for studies involving LIDAR measurements. Measurement physics and processing is discussed in context of errors associated with terrain, vegetation, and the snow surface. Recommendations for measurement surveying is also provided.

Hedrick, A., H.-P. Marshall, A. Winstral, K. Elder, S. Yueh, and D. Cline. “Independent Evaluation of the SNODAS Snow Depth Product Using Regional-Scale Lidar-Derived Measurements.” *The Cryosphere* 9.1 (2015): 13–23.

Shows how LIDAR data can be used to validate the outputs of an operational snowpack modeling and measurement system (SNODAS, the SNOw Data Assimilation System). Errors associated with different geographic areas are identified and analyzed.

Hopkinson, C., T. Collins, A. Anderson, J. Pomeroy, and I. Spooner. “Spatial Snow Depth Assessment Using LiDAR Transect Samples and Public GIS Data Layers in the Elbow River Watershed, Alberta.” *Canadian Water Resources Journal* 37.2 (2012): 69–87.

Classic case study indicating how airplane-deployed LIDAR can be used to characterize variability in snow depth for the Elbow River Watershed that provides water to the City of Calgary, Alberta, Canada. Flight line planning, acquisition time, data analysis, and extrapolation is provided. Spatial estimation of SWE is demonstrated.

Hopkinson, C., M. Sitar, L. Chasmer, and P. Treitz. "Mapping Snowpack Depth beneath Forest Canopies Using Airborne Lidar." ***Photogrammetric Engineering & Remote Sensing*** **70.3 (2004): 323–330.**

Indicates how a LIDAR system mounted on an airplane can be used for measurement of snow depth in a forested area. Difficulties associated with the forest canopy are identified and discussed, although the LIDAR measurements were suitable for showing trends and variability in snow accumulation.

Painter, T. H., D. F. Berisford, J. W. Boardman, et al. "The Airborne Snow Observatory: Fusion of Scanning Lidar, Imaging Spectrometer, and Physically-Based Modeling for Mapping Snow Water Equivalent and Snow Albedo." ***Remote Sensing of Environment*** **184 (2016): 139–152.**

This paper describes an important airborne LIDAR and remote sensing platform where LIDAR is used to determine surface elevation and subsequent snow depth along with concomitant albedo measurements made by an imaging spectrometer. The snow depth raster datasets were used to determine SWE utilizing associated snow densities obtained from a snowpack evolution model. This study describes the first airborne snow observatory that incorporated multiple sensors for operational spatial measurements of snow variability.

Terrestrial Laser Scanning (TLS)

TLS is a LIDAR system deployed on the ground at a fixed position and is to be contrasted to airborne LIDAR systems. Deems, et al. 2013 describes the geometry of a TLS system. Prokop 2008 discusses the accuracy and precision of TLS in the context of measurement physics and is useful for understanding the operational limitations of these systems. Filhol and Sturm 2015 is essential reading for understanding how to deploy and use LIDAR devices at a field location for measurement of the snow surface.

Deems, J. S., T. H. Painter, and D. C. Finnegan. "Lidar Measurement of Snow Depth: A Review." ***Journal of Glaciology*** **59.215 (2013): 467–479.**

Although this paper has a strong focus on airborne LIDAR, the authors describe the system geometry of a ground-based TLS system.

Filhol, S., and M. Sturm. "Snow Bedforms: A Review, New Data, and a Formation Model." ***Journal of Geophysical Research: Earth Surface*** **120.9 (2015): 1645–1669.**

This paper reviews the morphology of snow surface features, indicating how TLS can be used to obtain shape and spatial variability. The authors show how length, width, and height relationships of snow surface features can be obtained and related to the dynamics of wind-redistributed snow.

Prokop, A. "Assessing the Applicability of Terrestrial Laser Scanning for Spatial Snow Depth Measurements." ***Cold Regions Science and Technology*** **54.3 (2008): 155–163.**

Describes the optimal environmental conditions required for reducing error and increasing the accuracy of LIDAR measurements in avalanche areas. Effects of wavelength, snow surface particle size, and solar radiation on the LIDAR scans are extensively discussed.

Radar

Marshall and Koh 2008 provides a historical overview of how Frequency Modulated Continuous Wave (FMCW) radars are used for snowpack stratigraphy. Papers that clearly present the theory and applications of FMCW radar are Marshall, et al. 2004 and Yankielun, et al. 2004. Above-snow and buried antenna measurement devices are shown by Gubler and Hiller 1984 whereas Schmid, et al. 2014 describes a below-snow FMCW system for continuous measurements of snowpack evolution. Richardson, et al. 1997 indicates how FMCW radars can be deployed on an all-terrain vehicle to measure snow along transects.

Gubler, H., and M. Hiller. "The Use of Microwave FMCW Radar in Snow and Avalanche Research." ***Cold Regions Science and Technology*** **9.2 (1984): 109–119.**

A classic paper that clearly describes the theory and application of Frequency Modulated Continuous Wave (FMCW) radar to measure snow depth and the distance to layers in the snowpack for determination of stratigraphy. Radar antennas buried beneath the snowpack and deployed above the snow surface are described in the context of determining snow depth and snowpack properties utilizing semi-empirical relationships.

Marshall, H.-P., and G. Koh. "FMCW Radars for Snow Research." ***Cold Regions Science and Technology*** **52.2 (2008): 118–131.**

An extensive overview of the history and instrumentation associated with FMCW radars used for measurement of snowpack stratigraphy. Mounting platforms, imaging, and deployment of these radar devices are described and discussed along with an overview of the theory involving multiple reflectors and radar resolution.

Marshall, H.-P., G. Koh, and R. R. Forster. "Ground-Based Frequency-Modulated Continuous Wave Radar Measurements in Wet and Dry Snowpacks, Colorado, USA: An Analysis and Summary of the 2002–03 NASA CLPX data." ***Hydrological Processes*** **18.18 (2004): 3609–3622.**

Describes FMCW radar measurements collected as part of the NASA Cold Land Processes (CLPX) experiment. A basic overview of the theory and measurements made at different frequency bands are also provided. The authors identify that excessive attenuation of the radar signal occurs for higher frequencies when liquid water content is high. However, higher frequencies can provide greater resolution and identification of snowpack layers compared to lower frequencies.

Richardson, C., E. Aarholt, S.-E. Hamran, P. Holmlund, and E. Isaksson. "Spatial Distribution of Snow in Western Dronning Maud Land, East Antarctica, Mapped by a Ground-Based Snow Radar." ***Journal of Geophysical Research: Solid Earth*** **102.B9 (1997): 20343–20353.**

Describes an FMCW radar device attached to an all-terrain vehicle used to obtain snow depth and stratigraphy over a transect. Snow layers and the speed of electromagnetic wave propagation in snow and ice is discussed. The variability in snow layer thickness is identified over the transect, relating the visibility of individual snow layers in the radar transect to geographic location, accumulation, and the presence of wind distribution processes.

Schmid, L., A. Heilig, C. Mitterer, et al. "Continuous Snowpack Monitoring Using Upward-Looking Ground-Penetrating Radar Technology." ***Journal of Glaciology*** **60.221 (2014): 509–525.**

The paper shows how changes in snowpack layering can be measured using a commercial monopulse radar system installed in an enclosure at the bottom of the snowpack. A dual-frequency radar system was utilized to measure changes in snowpack layering at times of ablation when high levels of liquid water content caused attenuation.

Yankielun, N., W. Rosenthal, and R. E. Davis. "Alpine Snow Depth Measurements from Aerial FMCW Radar." ***Cold Regions Science and Technology*** **40.1–2 (2004): 123–134.**

Describes the theory and instrumentation associated with an experiment where an FMCW radar was mounted on a ski gondola and used to measure snow depth at a site located at Mammoth Mountain, California. Comparisons were made with ground truth data obtained from depth rods.

UAVs and Near-Surface Remote Sensing

Blyth, et al. 1974 used stationary cameras to measure snow depth. Bühler, et al. 2015 and Goetz and Brenning 2019 utilized unmanned aerial vehicles (UAVs) to measure snow depth at field sites in the Alps. Marti, et al. 2016 deployed UAVs to measure snow depth in the Pyrenees mountains of France. De Michele, et al. 2016 measured snow depth at an alpine site in northern Italy, whereas Fernandes, et al. 2018 performed a similar study at sites in eastern Canada. Harder, et al. 2016 assessed the accuracy of snow depth estimation at prairie field sites with stubble and at alpine field sites with complex topography. Hawley and Millstein 2019 measured the depth of snow drifts at Summit Station, Greenland, for a civil engineering application related to snow removal. Vander Jagt, et al. 2015 compared the ability for different processing algorithms to determine snow depth for a field site in Tasmania, Australia. Nolan, et al. 2015 developed a novel low-cost system for UAV measurement of snow depth and used the system to measure snow on an ice-covered river near Fairbanks, Alaska. Photogrammetric techniques involving UAVs utilize Structure-From-Motion (SfM) algorithms for determination of snow depth.

Blyth, K., M. a. R. Cooper, N. E. Lindsey, and R. B. Painter. “Snow Depth Measurement with Terrestrial Photos.” *Photogrammetric Engineering* 40.8 (1974): 937–942.

Indicates how ground-based stationary cameras with overlapping fields of view can be used to measure snow depth. Stationary markers visible in the images provide a means for camera calibration. Although the basic analysis was conducted using a stereoplotter to aid in manual interpretation, the paper provides information useful for computer algorithm adaptation of the technique.

Bühler, Y., M. Marty, L. Egli, et al. “Snow Depth Mapping in High-Alpine Catchments Using Digital Photogrammetry.” *The Cryosphere* 9.1 (2015): 229–243.

Shows how a line scanner sensor can be used to obtain digital surface models (DSMs) of the snow surface in Switzerland. Comparisons were made between line scanner, ground-truth snow rod data, and point measurements made using GPS receivers.

De Michele, C., F. Avanzi, D. Passoni, et al. “Using a Fixed-Wing UAS to Map Snow Depth Distribution: An Evaluation at Peak Accumulation.” *The Cryosphere* 10.2 (2016): 511–522.

Describes flights made with a small drone (SenseFly) and a single visible camera used to obtain overlapping images of the Val Grosina Valley in northern Italy. Survey design and digital surface model (DSM) production during post-processing are described along with the effects of spatial sampling of ground truth data.

Fernandes, R., C. Prevost, F. Canisius, et al. “Monitoring Snow Depth Change across a Range of Landscapes with Ephemeral Snowpacks Using Structure from Motion Applied to Lightweight Unmanned Aerial Vehicle Videos.” *The Cryosphere* 12.11 (2018): 3535–3550.

A small drone with a single camera (Phantom Pro 3 Plus UAV) was used to obtain images to create DSMs of snow-free and snow-covered land surface areas at sites situated in two regions of eastern Canada. Data from seventy-one flights was used to quantify accuracy and uncertainty in point clouds based on altitude, location, topography, snowpack metamorphism, and vegetation.

Goetz, J., and A. Brenning. “Quantifying Uncertainties in Snow Depth Mapping from Structure from Motion Photogrammetry in an Alpine Area.” *Water Resources Research* 55.9 (2019): 7772–7783.

Describes experiments involving a UAV deployed in the Alps to quantify uncertainties when measuring snow depth using DSMs derived from overlapping camera images. A statistical threshold for a minimum detected snow depth at a confidence level of 95 percent was introduced based on the standard deviations of DSMs corresponding to snow-covered and snow-free conditions. This allows for quantification of data uncertainty when measuring shallow snowpacks with UAVs.

Harder, P., M. Schirmer, J. Pomeroy, and W. Helgason. “Accuracy of Snow Depth Estimation in Mountain and Prairie Environments by an Unmanned Aerial Vehicle.” *The Cryosphere* 10.6 (2016): 2559–2571.

A small UAV (SenseFly Ebee) was deployed at prairie and alpine locations. Assessment of snow depth accuracy showed that errors were larger at prairie field locations with tall stubble, whereas short stubble locations had a similar accuracy to sites in the mountains. Errors included shading of the snow surface by stubble on the prairies and the reflection of light from south-facing snow patches in complex terrain.

Hawley, R. L., and J. D. Millstein. "Quantifying Snow Drift on Arctic Structures: A Case Study at Summit, Greenland, Using UAV-Based Structure-from-Motion Photogrammetry." ***Cold Regions Science and Technology*** **157 (2019): 163–170.**

UAV Structure-from-motion (SfM) photogrammetry was used to quantify patterns of drifting snow accumulation around a building at Summit Station, Greenland. The volume of snow determined from the DSMs provided inputs for civil engineering calculations utilized to estimate snow removal time and associated costs for infrastructure management.

Marti, R., S. Gascoin, E. Berthier, M. de Pinel, T. Houet, and D. Laffly. "Mapping Snow Depth in Open Alpine Terrain from Stereo Satellite Imagery." ***The Cryosphere*** **10.4 (2016): 1361–1380.**

Stereo-pair images collected using the Pléiades-1A and 1B satellites were compared with near-surface images captured using a camera affixed to a small UAV (SenseFly Ebee) in the Bassiès catchment of the Pyrenees mountains of France. The paper clearly describes signal processing for satellite and near-surface images. Comparisons were made between satellite and UAV images showing effects of biases and shadows at different scales.

Nolan, M., C. Larsen, and M. Sturm. "Mapping Snow Depth from Manned Aircraft on Landscape Scales at Centimeter Resolution Using Structure-from-Motion Photogrammetry." ***The Cryosphere*** **9.4 (2015): 1445–1463.**

The authors of this paper developed a low-cost photogrammetry system using off-the-shelf commercial camera hardware and a survey-grade GPS receiver. Mounted on an airplane, the system was used to obtain photographic data. Comparisons related to accuracy and precision were made with respect to vegetation and sampling methodology at locations on an ice-covered river, in valleys, and on river islands.

Vander Jagt, B., A. Lucieer, L. Wallace, D. Turner, and M. Durand. "Snow Depth Retrieval with UAS Using Photogrammetric Techniques." ***Geosciences*** **5.3 (2015): 264–285.**

Describes how a small octocopter was used in an alpine environment at Mount Field National Park (Tasmania, Australia) to determine snow depth. A survey-grade GPS measured the elevation of the snow surface to determine snow depth for comparisons. The paper contains a detailed description of the algorithms used for photogrammetry. Processing techniques were applied to remove vegetation effects. Two different processing methods were evaluated for determination of snow depth.

GPS

Hejcman, et al. 2006 utilized Global Positioning System (GPS) receivers to determine snow depth by measurement of snow surface elevation. Larson, et al. 2009 was the first to use the signal-to-noise (SNR) ratio of GPS signals to determine snow depth and the method was evaluated for operational use by Gutmann, et al. 2012. A theoretical analysis of GPS snow-depth reflectometry is presented by Nievinski and Larson 2014a and Nievinski and Larson 2014b. Larson and Nievinski 2013 identify terrain effects related to GPS snow-depth determination. McCreight, et al. 2014 measured snow depth by GPS signals and related the resulting measurements to snow density and snow water equivalent (SWE) using empirical models. Ozeki and Heki 2012 formulated a novel method to determine snow depth using GPS signals and this method is not dependent on the satellite-receiver geometry.

Gutmann, E. D., K. M. Larson, M. W. Williams, F. G. Nievinski, and V. Zavorotny. "Snow Measurement by GPS Interferometric Reflectometry: An Evaluation at Niwot Ridge, Colorado." ***Hydrological Processes*** **26.19 (2012): 2951–2961.**

This paper describes tests of a system utilizing L2 band GPS signals to determine snow depth at a field site in Colorado. Ground-based measurements with a stationary LIDAR device are used for comparison.

Hejcman, M., I. J. Dvorak, M. Kocianova, et al. “Snow Depth and Vegetation Pattern in a Late-Melting Snowbed Analyzed by GPS and GIS in the Giant Mountains, Czech Republic.” *Arctic, Antarctic, and Alpine Research* 38.1 (2006): 90–98.

The authors show how survey-grade GPS measurements can be utilized to determine the elevation of the snow and ground surface at a given latitude and longitude. The snow depth and ablation rate are found by taking the difference between GPS points sampled at different times.

Larson, K. M., E. D. Gutmann, V. U. Zavorotny, J. J. Braun, M. W. Williams, and F. G. Nievinski. “Can We Measure Snow Depth with GPS Receivers?” *Geophysical Research Letters* 36.17 (2009).

This important paper was the first to relate GPS L2 band signals to snow depth. A model of multipath GPS electromagnetic wave propagation was used to relate the signal-to-noise ratio (SNR) of GPS satellite signals to snow depth. An existing model of GPS signal interaction with soil was modified with a snow layer. Comparisons were made with ultrasonic and depth rod observations of snow depth.

Larson, K. M., and F. G. Nievinski. “GPS Snow Sensing: Results from the EarthScope Plate Boundary Observatory.” *GPS Solutions* 17.1 (2013): 41–52.

The paper demonstrated that GPS networks currently utilized for geodetic applications can be used to obtain snow depth data over an area of 1000 m^2 using L2 band signals. Geographic considerations of sites are analyzed with respect to terrain slope and GPS signal multipath reflections.

McCreight, J. L., E. E. Small, and K. M. Larson. “Snow Depth, Density, and SWE Estimates Derived from GPS Reflection Data: Validation in the Western U.S.” *Water Resources Research* 50.8 (2014): 6892–6909.

Demonstrates how snow depth obtained from L2 band GPS signals can be used along with empirical models to determine snow density and SWE. The paper contains an important analysis of the GPS antenna snow sampling footprint. Extensive ground truth data is used for validation.

Nievinski, F. G., and K. M. Larson. “Inverse Modeling of GPS Multipath for Snow Depth Estimation—Part I: Formulation and Simulations.” *IEEE Transactions on Geoscience and Remote Sensing* 52.10 (2014a): 6555–6563.

This paper contains a readable description of the forward and inverse mathematical models used to measure snow depth data using L2 band GPS signals. Biases and the inverse model are described, and reflector height uncertainties and errors are quantified.

Nievinski, F. G., and K. M. Larson. “Inverse Modeling of GPS Multipath for Snow Depth Estimation—Part II: Application and Validation.” *IEEE Transactions on Geoscience and Remote Sensing* 52.10 (2014b): 6564–6573.

A companion to the Nievinski and Larson 2014a paper, this paper discusses operational considerations associated with satellite elevation and snow depth (reflector) height. Tests conducted using GPS receivers at forested, grassland, and alpine sites are used for validation of the technique.

Larson, K. M., and E. E. Small. “Estimation of Snow Depth Using L1 GPS Signal-to-Noise Ratio Data.” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 9.10 (2016): 4802–4808.

Most other papers on GPS reflectometry used to obtain snow depth utilized L2 band signals. The L2 band signals are a newer addition to the GPS satellite network. To reconstruct snow depth using L1 band GPS signals, the authors address the influence of noise in the L1 band signals as compared to the newer L2 band signals. The accuracy of snow depths obtained using these L1 band signals is assessed.

Ozeki, M., and K. Heki. "GPS Snow Depth Meter with Geometry-Free Linear Combinations of Carrier Phases." ***Journal of Geodesy*** **86.3 (2012): 209–219.**

This paper described the first experiments that utilized L4 band GPS data to obtain snow depth. Although L4 band signals have been utilized to measure the ionosphere, the authors show that the L4 band signals can be used to determine snow depth with an error of ~10 cm analogous to GPS reflectometry measurements of snow depth utilizing L1 and L2 band signals.

Density

Gravimetric methods utilize the mass of snow in a sample volume to determine density. Dielectric and Radar and GPS devices rely on interaction of electromagnetic waves with snow, whereas Acoustic devices are dependent on sound waves interacting with the snowpack as an air-filled porous medium.

Gravimetric

Historical perspectives on the use of gravimetric samplers for snowpack measurement can be found in Seligman 1936 and Radionov, et al. 1997. Gary 1967 discusses the physics of snow sampler insertion into the snowpack. Studies comparing the use of different samplers are presented by Conger and McClung 2009 as well as Crook and Freeman 1973. Granberg and Kingsbury 1984 and Perla, et al. 1982 demonstrate the use of scoop samplers to measure snow density from samples extracted from the walls of snowpits.

Conger, S. M., and D. M. McClung. "Comparison of Density Cutters for Snow Profile Observations." ***Journal of Glaciology*** **55.189 (2009): 163–169.**

Three different gravimetric measurement samplers ("cutters") were tested in the Rocky Mountains of British Columbia at the same field site. Errors and differences were identified between wedge and tube samplers. Although all samplers produced values within an 11 percent error, operator effects associated with partial filling of the sampler were identified.

Crook, A. G., and T. G. Freeman. "A Comparison of Techniques of Sampling the Arctic-Subarctic Snowpack in Alaska." ***Proceedings of the Western Snow Conference*** **41 (1973):62–68.**

Two different gravimetric snow samplers and sampling methods (snowtube and snowpit circular cutter samplers) were tested along a snowcourse and compared for differences. The authors present an error analysis that demonstrates a correlation between errors and snow density. The errors between snowtube and snowpit measurements were reduced when average snow densities increased, demonstrating effects of crystal structure and depth hoar on the measurements.

Gary, H. L. "Density Variation in a Snowpack of Northern New Mexico." ***Proceedings of the Western Snow Conference*** **35 (1967): 6–10.**

The paper compares different circular snow samplers to measure snow density in snowpits. Friction coefficients for plastic snow samplers are higher, thereby increasing the amount of force required to insert the tube, but the transparent plastic allows for the snow surveyor to view whether the sample contains a mixture of snow and organic material or air voids in the sample. Metal snow samplers are stated to be more durable than samplers created from plastic.

Granberg, H. B., and C. M. Kingsbury. "Tests of New Snow Density Samplers." ***Proceedings of the Eastern Snow Conference*** **41 (1984): 224–228.**

The authors describe two snow samplers that have triangular and circular designs. The “Granberg-Crocker” (G-C) sampler described in this paper allows for samples to be extracted at progressive distances into the wall of the snowpit.

Perla, R., T. M. H. Beck, and T. T. Cheng. “The Shear Strength Index of Alpine Snow.” *Cold Regions Science and Technology* 6 (1982): 11–20.

The authors describe the use of an oval tube inserted into the side of a snowpit to measure snow density. The thickness of the oval tube was 2 cm and the authors determine that samplers with a smaller dimension cannot be used for snowpit sampling, despite layers of smaller thickness often existing within a snowpit.

Radionov, V. F., N. N. Bryazgin, E. I. Alexandrov, I. Solovyova, T. C. Grenfell, and University of Washington. *The Snow Cover of the Arctic Basin*. Seattle: Applied Physics Laboratory, University of Washington, 1997.

A report that provides a description of snow samplers and measurement balances used by Russian scientists in the 20th century to determine snow density.

Seligman, G. *Snow Structure and Ski Fields: Being an Account of Snow and Ice Forms Met with in Nature, and a Study on Avalanches and Snowcraft*. London: Macmillan, 1936.

Provides a historical perspective on snow samplers used to measure snow density in the early 20th century.

Dielectric and Radar

The papers in this section have a strong focus on the use of electromagnetic waves to measure snow density. For other papers where density is determined as a precursor for computation of snow water equivalent utilizing electromagnetic waves, please see Radar and GPS in the Snow Water Equivalent section. Niang, et al. 2003 describes a measurement device consisting of a ribbon cable antenna situated through the snowpack. The “Finnish Snow Fork” with two metal prongs inserted into the snowpack was first described by Sihvola and Tiuri 1986, whereas Tiuri, et al. 1984 provides theoretical background for device operation. Stein, et al. 1997 were the first investigators to adapt time-domain reflectometry (TDR) for measurement of snow density. Schmid, et al. 2014 used upward-looking ground-penetrating radar (GPR) and an inverse model to determine snow density.

Niang, M., M. Bernier, Y. Gauthier, et al. “On the Validation of Snow Densities Derived from SNOWPOWER Probes in a Temperate Snow Cover in Eastern Canada: First Results.” *Proceedings of the Eastern Snow Conference* 60 (2003): 175–187.

The paper describes a novel circuit that sends electromagnetic waves through a ribbon cable at different frequencies. A model of electromagnetic wave interaction is used to estimate snow density and liquid water content. Impedance discontinuities at the air-snow and ground-snow interfaces have the potential to affect this measurement technique.

Schmid, L., A. Heilig, C. Mitterer, et al. “Continuous Snowpack Monitoring Using Upward-Looking Ground-Penetrating Radar Technology.” *Journal of Glaciology* 60.221 (2014): 509–525.

The authors describe a system that measures bulk snow density using a radar device situated in an enclosure beneath the snowpack. The speed of electromagnetic waves in the medium was related to snow density. The inverse model utilized a layered approach to determine an overall speed over the height of snow.

Sihvola, A., and M. Tiuri. “Snow Fork for Field Determination of the Density and Wetness Profiles of a Snow Pack.” *IEEE Transactions on Geoscience and Remote Sensing*, *GE*-24.5 (1986): 717–721.

The “Finnish” snow fork consists of two prongs inserted into the snowpack. A resonator attached to a transmission line connected to the prongs is used to measure changes in frequency and attenuation to determine the permittivity of snow when the prongs are inserted into the snow surface or into the side of a snowpit. Empirical relationships between snow permittivity, density, and liquid water content are used to obtain measurements.

Stein, J., G. Laberge, and D. Lévesque. “Monitoring the Dry Density and the Liquid Water Content of Snow Using Time Domain Reflectometry (TDR).” *Cold Regions Science and Technology* 25.2 (1997): 123–136.

TDR probes are widely used to determine the liquid water content of soil. The TDR measurement device consists of two prongs analogous to the Finnish snow fork described by Sihvola and Tiuri 1986. Stein, et al. 1997 describes the physics and empirical relationships between permittivity, snow density, and liquid water content. The effects of probe spacing and attenuation related to liquid water are described and discussed.

Tiuri, M. E., A. H. Sihvola, E. Nyfors, and M. Hallikaiken. “The Complex Dielectric Constant of Snow at Microwave Frequencies.” *IEEE Journal of Oceanic Engineering* 9.5 (1984): 377–382.

The authors relate the relative permittivity of snow to density and liquid water content based on snow structure and frequencies ranging from 850 MHz to 12.6 GHz. Electromagnetic theory and semi-empirical equations make this paper a useful companion to the Sihvola and Tiuri 1986 paper.

Acoustic

Using an inverse model and geophysical methods, Albert 1993 showed how acoustic impulses propagating horizontally over a snow-covered field can determine snow depth and density. Marco, et al. 1998 utilized an impedance tube to relate the acoustic impedance of a snow sample to snow density. Kinar and Pomeroy 2015 demonstrated how audible waves can determine snow density, whereas Lieblappen, et al. 2020 show how angular reflection coefficients obtained from ultrasonic waves can measure porosity and snow density.

Albert, D. G. *Attenuation of Outdoor Sound Propagation Levels by a Snow Cover* (CRREL Report No. 93–20). Hanover, NH: U. S. Army Corps of Engineers, 1993.

The report demonstrates a novel experiment where impulses created by a pistol in the air medium above a snowpack are sensed by microphones and geophones to measure the acoustic response of a snow-covered field. The Biot theory of sound propagation through porous media is applied to the data and an inverse model is used to determine snowpack properties including porosity and density.

Kinar, N. J., and J. W. Pomeroy. “SAS2: The System for Acoustic Sensing of Snow.” *Hydrological Processes* 29.18 (2015): 4032–4050.

The authors of this paper introduce a unified model of sound propagation through snow based on the Biot theory of sound wave propagation through porous media. A frequency-domain inverse model based on the speed and attenuation of sound waves in snow determined snow density, liquid water content, and temperature. A custom electronic circuit was created to send sound waves into snow, receive reflections, and provide inputs to the inverse model.

Lieblappen, R., J. M. Fegyveresi, Z. Courville, and D. G. Albert. “Using Ultrasonic Waves to Determine the Microstructure of Snow.” *Frontiers in Earth Science* 8 (2020): 34.

Shows how ultrasonic waves at a frequency of 90 kHz can be used to determine the porosity of snow samples in a laboratory. A high-frequency sound-wave approximation was utilized where the speed of sound in snow is constant above a threshold frequency. Transducers were placed at different angles to a snow sample and angular-dependent reflection coefficients utilized to determine porosity estimates that can be related to snow density.

Marco, O., O. Buser, P. Villemain, F. Touvier, and H. P. Revol. “Acoustic Impedance Measurement of Snow Density.” *Annals of Glaciology* 26 (1998): 92–96.

The paper describes an experiment where snow is placed in an impedance tube with an acoustic source. In a similar fashion to other classic acoustic material characterization experiments, two condenser microphones inside of the tube are used to measure impedance. The absolute value of the complex acoustic impedance was related to porosity. Porosity is then directly related to snow density.

Snow Water Equivalent

Gravimetric methods of determining snow water equivalent (SWE) utilize snow tubes to extract samples from the snowpack, snow pillows to measure pressure, or precipitation gauges for measurement of snowfall. Radar and GPS measurements involve electromagnetic waves interacting with the snowpack and associated models that relate depth and density to SWE. Measurement devices involving Radioactivity utilize artificial isotopes or natural radioactive sources associated with soil or cosmic rays. Snow attenuates particles from the radioactive source and the resulting reduction in particle counts is related to SWE by an empirical calibration curve. Estimates of background radiation particle counts during the snow-free season is required. Acoustic methods utilize sound waves. Satellite Remote Sensing methods involve processing of data from sensors deployed on satellites and are suitable large-scale areal estimates of SWE.

Gravimetric

Modern metric snowtubes widely used for measurement of SWE along a transect are described by Farnes, et al. 1980 and Farnes, et al. 1982. Turčan and Loijens 1975 discusses factors that influence errors associated with snow tube sampling. Dixon and Boon 2012 provides a recent comparison between snowtube measurements and snowpit samples used to determine SWE. Beaumont 1965 provides an example of an antifreeze-filled snow pillow that was nominally installed at a stationary field site location during the mid-20th century, whereas Johnson, et al. 2015 describes a more reliable solid-state weighing device.

Beaumont, R. T. “Mt. Hood Pressure Pillow Snow Gage.” *Journal of Applied Meteorology* 4.5 (1965): 626–631.

The author provides a classic case study describing the design and deployment of a snow pillow used to measure SWE by the overlying pressure of an accumulated snowpack. Manufactured from rubber and filled with antifreeze, the device can be prone to mechanical failure.

Dixon, D., and S. Boon. “Comparison of the SnowHydro Snow Sampler with Existing Snow Tube Designs.” *Hydrological Processes* 26.17 (2012): 2555–2562.

The authors compare three different snow tubes with gravimetric snow pit measurements at the Star Creek Watershed in Alberta, Canada. Measurements were collected over grids situated in forested and clear-cut areas. Snowtubes were found to underestimate SWE compared to snowpits due to loss of snow from the tube.

Farnes, P. E., B. E. Goodison, N. R. Peterson, and R. P. Richards. “Proposed Metric Snow Samplers.” *Proceedings of the Western Snow Conference* 48 (1980): 107–119.

The paper provides proposed dimensions and initial tests of a metric snow sampler that is widely used for gravimetric sampling. The paper provides insight into the design criteria of metric snow samplers developed by a committee of snow scientists associated with the Western Snow Conference.

Farnes, P. E., N. R. Peterson, B. E. Goodison, and R. P. Richards. “Metrification of Manual Snow Sampling Equipment.” *Proceedings of the Western Snow Conference* 50 (1982): 120–132.

The authors provide a complete mechanical diagram of a commonly-used metric snowtube with a sharpened cutter end. The cutter is designed to penetrate the snowpack to extract a snow sample and can obtain a “plug” of vegetation or soil to ensure that snow is not lost from the bottom of the snowtube when a snow sample is extracted from the snowpack. A calibrated scale is used to determine SWE.

Johnson, J. B., A. B. Gelvin, P. Duvoy, G. L. Schaefer, G. Poole, and G. D. Horton. “Performance Characteristics of a New Electronic Snow Water Equivalent Sensor in Different Climates.” *Hydrological Processes* 29.6 (2015) 1418–1433.

The authors introduce a loadcell-based device suitable for replacing an antifreeze-filled snow pillow. Loadcells are more resilient and not as prone to mechanical failure. The paper shows design, deployment, and testing of the device.

Turčan, J., and H. S. Loijens. “Accuracy of Snow Survey Data and Errors in Snow Sampler Measurements.” *Proceedings of the Eastern Snow Conference* 32 (1975): 2–11.

The authors demonstrate that movement of the snowtube through the snowpack during sampling can introduce errors due to snow compaction, ice layers, and mechanical disaggregation. The authors introduce a mathematical analysis of errors.

Radar

Marshall, et al. 2005 demonstrates how SWE can be determined using frequency modulated continuous wave (FMCW) radar. Schmid, et al. 2014 utilizes an upward-looking monopulse ground penetrating radar (GPR) system, whereas Bradford, et al. 2009; Sundström, et al. 2013 Webb 2017; and St. Clair and Holbrook 2017 utilize above-snow GPR. Leinss, et al. 2015 describes a novel ground-based radar interferometry system for measurement of SWE.

Bernier, M., J.-P. Dedieu, Y. Duguay, and G. Seguin. “Snow Water Equivalent Estimation Using High Resolution SAR Data.” *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (2017): 1351–1354.

Provides a high-level overview of Synthetic Aperture Radar (SAR) algorithms used to measure SWE. The data requirements and frequencies of different methods are described and discussed.

Bradford, J. H., J. T. Harper, and J. Brown. “Complex Dielectric Permittivity Measurements from Ground-Penetrating Radar Data to Estimate Snow Liquid Water Content in the Pendular Regime.” *Water Resources Research* 45.8 (2009).

This paper describes the basic theory related to how monopulse ground penetrating radar (GPR) can be used to determine SWE. Semi-empirical relationships between permittivity, density, and liquid water content are identified along with relationships of speed and attenuation of electromagnetic waves in snow. Tests were conducted on shallow and wet snowpacks and signal processing of the GPR data is extensively discussed.

Holbrook, W. S., S. N. Miller, and M. A. Provart. “Estimating Snow Water Equivalent over Long Mountain Transects Using Snowmobile-Mounted Ground-Penetrating Radar.” *Geophysics* 81.1 (2016): WA183–WA193.

The authors mounted a monopulse GPR radar system on the front of a snowmobile in lieu of a towed sled to measure undisturbed snow. The real part of snow-relative permittivity was related to snow density by an empirical polynomial relationship. Errors in migration focusing were related to measurement of SWE along the transect lines where GPR data was collected.

Leinss, S., A. Wiesmann, J. Lemmetyinen, and I. Hajnsek. “Snow Water Equivalent of Dry Snow Measured by Differential Interferometry.” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 8.8 (2015): 3773–3790.

This paper describes a system to determine SWE by a ground-based interferometry system. The system is comprised of two radar antennas with a rotating assembly where the elevation and azimuth angles can be set. Mounted on a 9 m tower at a field site, the system collected backscatter data that was used to obtain snow density. Phase differences from differential interferograms allowed for determination of SWE.

Marshall, H.-P., G. Koh, and R. R. Forster. “Estimating Alpine Snowpack Properties Using FMCW Radar.” *Annals of Glaciology* 40 (2005): 157–162.

This paper describes the theory of Frequency Modulated Continuous Wave (FMCW) radar along with four methods for determining SWE. Errors associated with each method are quantified and comparisons are made with snow pit measurements. Since an average of snowpack density was used for electromagnetic time-to-depth conversion, an experiment involving metal reflectors placed into the snowpack at various depths was used to quantify errors.

Schmid, L., A. Heilig, C. Mitterer, J. Schweizer, H. Maurer, R. Okorn, and O. Eisen. “Continuous Snowpack Monitoring Using Upward-Looking Ground-Penetrating Radar Technology.” *Journal of Glaciology* 60.221 (2014): 509–525.

A GPR radar device in an enclosure under the snowpack was used to determine average snow depth (height of snow) and density by an inverse model. The mathematical product of snow depth and density was used to calculate SWE. Comparisons were made with nearby snow pillow and snow pit measurements.

St. Clair, J., and W. S. Holbrook. “Measuring Snow Water Equivalent from Common-Offset GPR Records through Migration Velocity Analysis.” *The Cryosphere* 11.6 (2017): 2997–3009.

The authors establish a novel geophysical processing algorithm for extraction of SWE from GPR data. Digital filters were applied to reduce the influence of small variations in the snow layers and ground surface on reflections of the electromagnetic waves. The velocity of electromagnetic wave propagation in the snowpack was determined using the Dix equation. SWE data was related to relative permittivity using empirical relationships.

Sundström, N., D. Gustafsson, A. Kruglyak, and A. Lundberg. “Field Evaluation of a New Method for Estimation of Liquid Water Content and Snow Water Equivalent of Wet Snowpacks with GPR.” *Hydrology Research* 44.4 (2013): 600.

A procedure is described for determining SWE using a multipath model with two GPR radar signals. Measurement of snow depth, density, and liquid water content allowed for SWE to be computed using an effective density. Validation experiments were conducted in the Lake Korsvattnet watershed of Sweden.

Webb, R. W. “Using Ground Penetrating Radar to Assess the Variability of Snow Water Equivalent and Melt in a Mixed Canopy Forest, Northern Colorado.” *Frontiers of Earth Science* 11.3 (2017): 482–495.

SWE and snowpack stratigraphy in forested areas and clearings were measured by using GPR deployed along a transect. SWE variability determined from the GPR data was characterized using variograms and geostatistics.

Radioactivity

Morrison 1976 is a good example of how artificial radioisotopes were used for measurement of SWE in the mid-20th century. Bissell and Peck 1973 describes the basic theory and testing of a ground-based soil gamma radiation detector mounted above the snowpack. Wright, et al. 2011 describes more recent testing of a similar ground-based detector. Kodama, et al. 1979 was one of the first papers to describe an upward-looking cosmic ray sensor (CRS) situated under the snowpack to determine SWE. Gugerli, et al. 2019 describes a CRS progressively covered by snow on a glacier and provides an excellent overview of the measurement physics and data processing. Peck, et al. 1971 covers airborne deployment of gamma radiation detectors to measure SWE. Carroll and Carroll 1989a provides an error analysis of airborne gamma radiation detector measurements whereas Carroll and Carroll 1989b address the effects of gamma radiation emissions from vegetation on the overall calculated SWE along a transect. Cho, et al. 2020 is a recent analysis that provides up-to-date equations and operational descriptions of flight lines and data collection procedures for airborne gamma radiation measurement of SWE.

Bissell, V. C., and E. L. Peck. “Monitoring Snow Water Equivalent by Using Natural Soil Radioactivity.” *Water Resources Research* 9.4 (1973): 885.

The authors clearly demonstrate how gamma radiation counts from a detector affixed above the snow surface can be related to SWE using an empirical calibration curve derived from gravimetric SWE data collected at a nearby snowcourse. Background radiation counts from the snow-free soil is required for application of this method.

Carroll, S. S., and T. R. Carroll. “Effect of Uneven Snow Cover on Airborne Snow Water Equivalent Estimates Obtained by Measuring Terrestrial Gamma Radiation.” *Water Resources Research* 25.7 (1989a): 1505–1510.

Provides a statistical model that relates SWE variability along an airborne transect to the overall error associated with the gamma radiation method of SWE measurement. Detection of gamma radiation along a flight transect only allows for determination of an averaged value of SWE over spatial sections of the transect due to the time required for gamma radiation to travel through the snowpack and air relative to airplane speed.

Carroll, S. S., and T. R. Carroll. “Effect of Forest Biomass on Airborne Snow Water Equivalent Estimates Obtained by Measuring Terrestrial Gamma Radiation.” *Remote Sensing of Environment* 27.3 (1989b): 313–319.

The authors introduce empirical relationships relating gamma radiation counts to SWE and vegetation biomass. An error analysis indicates that the effects of biomass are more pronounced for deep snowpacks where radiation attenuation is higher.

Cho, E., J. M. Jacobs, and C. M. Vuyovich. “The Value of Long-Term (40 years) Airborne Gamma Radiation SWE Record for Evaluating Three Observation-Based Gridded SWE Data Sets by Seasonal Snow and Land Cover Classifications.” *Water Resources Research* 56.1 (2020).

This recent paper describes long-term comparisons between airborne gamma radiation datasets and gridded SWE data products obtained from remote sensing. Empirical relationships between gamma radiation particle counts and SWE are provided.

Gugerli, R., N. Salzmann, M. Huss, and D. Desilets. “Continuous and Autonomous Snow Water Equivalent Measurements by a Cosmic Ray Sensor on an Alpine Glacier.” *The Cryosphere* 13.12 (2019): 3413–3434.

Describes a case study demonstrating how a cosmic ray sensor (CRS) can be installed on a glacier to measure SWE. The CRS is placed on the glacier ice surface and is progressively covered by snow. The attenuation of cosmic ray neutrons by the snowpack is related to SWE. This paper describes the theory of measurement and presents a rigorous error analysis.

Kodama, M., K. Nakai, S. Kawasaki, and M. Wada. “An Application of Cosmic-Ray Neutron Measurements to the Determination of the Snow-Water Equivalent.” *Journal of Hydrology* 41.1 (1979): 85–92.

This is one of the first classic papers to popularize the use of cosmic ray sensors (CRS) to measure SWE. The authors provide empirical relationships enabling calculation of SWE from neutron counts obtained from an upward-looking detector situated underneath the snowpack.

Morrison, R. G. “Nuclear Techniques Applied to Hydrology.” *Proceedings of the Western Snow Conference* 44 (1976): 1–6.

Although active radioactive methods involving ionizing radiation have declined in use due to safety concerns, this paper describes the theory and operation of radioisotope gauges to determine SWE. These gauges were extensively used in the mid-20th century.

Peck, E. L., V. C. Bissell, E. B. Jones, and D. L. Burge. “Evaluation of Snow Water Equivalent by Airborne Measurement of Passive Terrestrial Gamma Radiation.” *Water Resources Research* 7.5 (1971): 1151–1159.

The authors describe the measurement physics and deployment of gamma radiation detectors on aircraft to measure SWE over large areas. Flights over a snow-free area is required to obtain background radiation counts. Although dated, this paper provides essential information on how gamma radiation can be measured using airborne detectors.

Wright, M., J. Kavanaugh, and C. Labine. “Performance Analysis of GMON3 Snow Water Equivalency Sensor.” *Proceedings of the Western Snow Conference* 79 (2011): 105–108.

This paper describes the operational tests of a commercial gamma radiation gauge suspended above the snowpack and used to determine a time series of SWE. The tests were conducted in the Rocky Mountains of Alberta, Canada, and at a site near Logan, Utah, in the United States.

GPS

McCreight, et al. 2014 demonstrates how above-ground Global Positioning System (GPS) receivers can determine snow depth. The resulting snow depth is related to density and SWE by an empirical model. Jacobson 2010 used an above-snow receiver with a two-layer snow and soil model to determine SWE. Steiner, et al. 2018 used a single below-snow receiver whereas Koch, et al. 2019 used receivers situated above and below the snow surface.

Jacobson, M. D. “Inferring Snow Water Equivalent for a Snow-Covered Ground Reflector Using GPS Multipath Signals.” *Remote Sensing* 2.10 (2010): 2426–2441.

The author implements a model utilizing L1 band GPS signals from an above-snow receiver to determine snow depth and density for determination of SWE. This is a two-layer model that also includes the effects of frozen soil.

Koch, F., P. Henkel, F. Appel, et al. “Retrieval of Snow Water Equivalent, Liquid Water Content, and Snow Height of Dry and Wet Snow by Combining GPS Signal Attenuation and Time Delay.” *Water Resources Research* (2019): 2018WR024431.

This paper was the first to describe a novel experiment involving GPS receivers situated above and below the snow surface that are used to simultaneously determine snowpack properties. A dielectric three-phase mixing model is used to simultaneously obtain snowpack properties from carrier-phase signals detected by the two GPS receivers. Snow-free reference signals are required for application of the technique.

McCreight, J. L., E. E. Small, and K. M. Larson. “Snow Depth, Density, and SWE Estimates Derived from GPS Reflection Data: Validation in the Western U.S.” *Water Resources Research* 50.8 (2014): 6892–6909.

Shows how a GPS antenna situated above the snowpack can be used to determine snow depth utilizing L2 band signals. SWE is determined using an empirical model that relates depth to density. The numerical product of snow depth and density is then used to compute SWE.

Steiner, L., M. Meindl, C. Fierz, and A. Geiger. “An Assessment of Sub-snow GPS for Quantification of Snow Water Equivalent.” *The Cryosphere* 12.10 (2018): 3161–3175.

Describes a simple model used to determine SWE from path delay propagation of L1 band GPS signals in snow. A single receiver placed under the snowpack is required. The paper compares different processing algorithms involving L1 band and L5 band signals.

Acoustic

Kinar and Pomeroy 2007 shows how audible frequency-swept acoustic waves produced in the air medium above the snowpack can be used to measure SWE.

Kinar, N. J., and J. W. Pomeroy. "Determining Snow Water Equivalent by Acoustic Sounding." *Hydrological Processes* 21.19 (2007): 2623–2640.

Describes how a frequency-swept acoustic source from 20 Hz to 20 kHz can be used with a recursive model of sound wave propagation through snow to determine SWE. The paper establishes a system composed of a loudspeaker and microphone pair situated above the snowpack to send sound waves into snow and to receive the reflections. The paper adapts theory from FMCW radar that uses similar frequency-swept source signals.

Satellite Remote Sensing

Pulliainen, et al. 2020 is useful for understanding how SWE is determined using remote sensing and is a good starting point for pedagogical use. Clifford 2010 provides a review of satellite SWE estimation methods and is useful for the selection of a suitable processing algorithm, whereas Mortimer, et al. 2020 provides a recent overview and comparison of remote sensing data products. Pardé, et al. 2007 utilizes an optimization algorithm with a model of snowpack physics to estimate SWE. Mote, et al. 2003 compares remote sensing estimates of SWE in central North America. SWE algorithms tested for sub-Arctic regions are presented by Walker and Silis 2002; Derksen, et al. 2010; and Gao, et al. 2010. Guan, et al. 2013 provides algorithms for Alpine and complex terrain.

Clifford, D. "Global Estimates of Snow Water Equivalent from Passive Microwave Instruments: History, Challenges and Future Developments." *International Journal of Remote Sensing* 31.14 (2010): 3707–3726.

A wide-ranging overview of how SWE is measured from satellites, indicating errors and uncertainties. Geographic differences between observations are also discussed. This paper is useful as a starting point for researchers who would like to measure SWE with remote sensing.

Derksen, C., P. Toose, A. Rees, et al. "Development of a Tundra-Specific Snow Water Equivalent Retrieval Algorithm for Satellite Passive Microwave Data." *Remote Sensing of Environment* 114.8 (2010): 1699–1709.

This was the first paper to propose a reliable algorithm for AMSR-E satellite measurement of SWE from passive microwave brightness in the sub-Arctic tundra. Temporal changes in a 37 GHz signal were related to SWE by ground-truth gravimetric data. This was the first study to show that SWE could be retrieved in a tundra environment from a single frequency band.

Gao, Y., H. Xie, N. Lu, T. Yao, and T. Liang. "Toward Advanced Daily Cloud-Free Snow Cover and Snow Water Equivalent Products from Terra–Aqua MODIS and Aqua AMSR-E Measurements." *Journal of Hydrology* 385.1 (2010): 23–35.

Tested at geographic locations in Alaska, the authors describe how ASMSR-E passive microwave observations of snow can be used along with visible imagery from MODIS to determine SWE. The algorithm relies on calibration of existing snow cover remote-sensing raster data products. A mathematical expression is provided to quantify the effects of cloud cover.

Guan, B., N. P. Molotch, D. E. Waliser, S. M. Jepsen, T. H. Painter, and J. Dozier. “Snow Water Equivalent in the Sierra Nevada: Blending Snow Sensor Observations with Snowmelt Model Simulations.” *Water Resources Research* 49.8 (2013): 5029–5046.

The authors clearly demonstrate how SWE can be determined from remote sensing data for regions with complex terrain. A physically based snowpack evolution model is used to constrain the remote sensing data and provide valid estimates of SWE in each remote sensing pixel.

Mortimer, C., L. Mudryk, C. Derksen, et al. “Evaluation of Long-Term Northern Hemisphere Snow Water Equivalent Products.” *The Cryosphere* 14.5 (2020): 1579–1594.

This paper contains a wide-ranging and recent comparison of raster SWE data products with snow course datasets serving as ground-truth data. Errors and limitations are discussed, and this makes the paper suitable for selecting a remote sensing technology for determination of SWE.

Mote, T. L., A. J. Grundstein, D. J. Leathers, and D. A. Robinson. “A Comparison of Modeled, Remotely Sensed, and Measured Snow Water Equivalent in the Northern Great Plains.” *Water Resources Research* 39.8 (2003).

With an explicit focus on the central region of North America, the authors compare microwave brightness temperatures from the Special Sensor Microwave/Imager (SSM/I) instrument to airplane passive gamma radiation measurements and SNTHERM snowpack evolution model outputs. Spatial and temporal errors are extensively discussed.

Pardé, M., K. Goïta, and A. Royer. “Inversion of a Passive Microwave Snow Emission Model for Water Equivalent Estimation Using Airborne and Satellite Data.” *Remote Sensing of Environment* 111.2–3 (2007): 346–356.

The authors demonstrate how a physically based microwave snowpack emission model can be used with an optimization algorithm to predict SWE from data collected by remote sensing platforms. Different model configurations were utilized, and uncertainties are described and discussed.

Pulliainen, J., K. Luojus, C. Derksen, et al. “Patterns and Trends of Northern Hemisphere Snow Mass from 1980 to 2018.” *Nature* 581.7808 (2020): 294–298.

This paper indicates how remote sensing can be used for determination of SWE estimates at a global scale and is useful as an introduction to remote sensing techniques. Spatial trends and bias corrections are discussed.

Walker, A. E., and A. Silis. “Snow-Cover Variations over the Mackenzie River Basin, Canada, Derived from SSM/I Passive-Microwave Satellite Data.” *Annals of Glaciology* 34 (2002): 8–14.

The authors show how SWE can be derived from SSM/I sensor data in the Mackenzie River basin of North America. The authors provide a useful overview of remote sensing model differences in relation to forested, flat prairie and tundra environments. Extensive ground truth datasets and analysis of geographic site conditions with respect to SWE algorithm performance make this paper useful for researchers who would like to determine SWE by remote sensing.

Liquid Water Content

Dielectric methods measure the electrical properties of snow to obtain the amount of liquid water present in the pore spaces of the snowpack. Chemical, Calorimetric, and Centrifugal techniques adapt physical chemistry methods for determination of snow liquid water content (LWC). GPS methods use electromagnetic waves from Global Positioning Satellites detected by near-surface receivers. Acoustic methods use sound waves for measurement of liquid water content.

Dielectric

Denoth 1989 and Avanzi et al. 2014 show how capacitance measurements can determine snow liquid water content. Denoth 1989 and Denoth 1999 describe measurements made with a snow sample placed in a holder between two horn antennas. Sihvola and Tiuri 1986 describes the Finnish Snow Fork device that is inserted into the snowpack to measure snow density and liquid water content using transmission line theory. Denoth 1994 describes the Denoth meter for determination of snow liquid water content, given concomitant measurements of bulk density. Techel and Pielmeier 2011 uses the Finnish Snow Fork and the Denoth meter to obtain spatial estimates of liquid water content. The theory of utilizing time-domain reflectometry (TDR) to measure snow liquid water content was presented by Stein, et al. 1997 whereas Lundberg 1997 addresses laboratory calibration of TDR probes for snow measurements. A stationary device with a ribbon cable used to determine liquid water content is described by Niang, et al. 2003.

Avanzi, F., M. Caruso, C. Jommi, C. De Michele, and A. Ghezzi. "Continuous-Time Monitoring of Liquid Water Content in Snowpacks Using Capacitance Probes: A Preliminary Feasibility Study." ***Advances in Water Resources*** **68 (2014): 32–41.**

The authors used commercial soil water content probes functioning as parallel-plate capacitors to measure the relative permittivity of snow. Time-domain reflectometry (TDR) probes were used as comparison devices. FEM model simulations of cylindrical capacitors, laboratory, and field testing validated the physical model introduced in this paper. Effects of snow-air gaps and sensor geometry are discussed.

Denoth, A. "Snow Dielectric Measurements." ***Advances in Space Research*** **9 (1989): 233–243.**

The author describes the theory and operation of parallel-plate and horn antenna-based snow liquid water content devices. Snow structure is related to snow dielectric properties for frequencies less than 10 GHz.

Denoth, A. "An Electronic Device for Long-Term Snow Wetness Recording." ***Annals of Glaciology*** **19 (1994): 104–106.**

This paper introduced the classic "Denoth meter" used to measure liquid water content. The system consists of a parallel-plate antenna that is inserted into the snowpack or into the side of a snowpit. Concomitant measurements of snow density (i.e., from gravimetric sampling) are required for application of an empirical relationship between electrical permittivity and water liquid content of snow. A twin-T bridge is used by the application circuit to measure capacitance.

Denoth, A. "Wet Snow Pendular Regime: The Amount of Water in Ring-Shaped Configurations." ***Cold Regions Science and Technology*** **30.1–3 (1999): 13–18.**

The author introduces a free-space measurement method involving microwave horn antennas situated at an angle to a snow sample. The influence of water on the electromagnetic wave is quantified.

Lundberg, A. "Laboratory Calibration of TDR-Probes for Snow Wetness Measurements." ***Cold Regions Science and Technology*** **25.3 (1997): 197–205.**

The authors indicate how TDR probes can be subjected to laboratory calibration for determination of snow liquid water content. The paper shows how the probes can be placed on a vertical pipe for measurement of liquid water content at various depths within the snowpack.

Niang, M., M. Bernier, Y. Gauthier, G. Fortin, E. Van Bochove, M. Stacheder, and A. Brandelik. "On the Validation of Snow Densities Derived from SNOWPOWER Probes in a Temperate Snow Cover in Eastern Canada: First Results." ***Proceedings of the Eastern Snow Conference*** **60 (2003): 175–187.**

Ribbon cable antennas situated throughout the snowpack were used to measure snow liquid water content and density. The ribbon cable antennas can be situated in a horizontal or diagonal fashion and are fastened to a frame. A model of electromagnetic wave interaction with the snowpack is used to obtain density and liquid water content.

Sihvola, A., and M. Tiuri. "Snow Fork for Field Determination of the Density and Wetness Profiles of a Snow Pack." ***IEEE Transactions on Geoscience and Remote Sensing*****, *GE*-24.5 (1986): 717–721.**

This classic paper described the Finnish snow fork for determination of snow density and liquid water content using transmission line theory. Unlike the Denoth meter introduced by Denoth 1994, the snow fork does not require concomitant measurements of snow density. Empirical relationships are utilized to determine liquid water content.

Stein, J., G. Laberge, and D. Lévesque. "Monitoring the Dry Density and the Liquid Water Content of Snow Using Time Domain Reflectometry (TDR)." ***Cold Regions Science and Technology*** **25.2 (1997): 123–136.**

This paper describes the theory of TDR as adapted to measure snow density and liquid water content. The effect of probe spacing as well as different empirical relationships are discussed. Data was collected at a field site situated in the Forêt Montmorency, Québec, Canada.

Techel, F., and C. Pielmeier. "Point Observations of Liquid Water Content in Wet Snow—Investigating Methodical, Spatial and Temporal Aspects." ***The Cryosphere*** **5.2 (2011): 405–418.**

This classic paper was the first extensively cited field study to use the Finnish snow fork to obtain spatial estimates of snow liquid water content in alpine environments of Switzerland. Horizontal and vertical measurements were collected throughout the snowpack. Contour and line plots of the data showed temporal meltwater propagation throughout the snowpack. Comparisons were also conducted using the Denoth 1994 wetness meter and the Sihvola and Tiuri 1986 snow fork.

Chemical, Calorimetric, and Centrifugal

Techniques involving an acid solution added to a snow sample are described by Davis, et al. 1985 and Boyne and Fisk 1990, whereas Davis and Dozier 1984 uses a florescent dye in a similar capacity. Calorimetric techniques involving a substance added to a snow sample to change the snow sample temperature are described by Halliday 1950; Jones 1979; Jones, et al. 1983; Fisk 1986; and Boyne and Fisk 1990. Centrifugal methods where water is separated from a snow sample by high-speed rotation is discussed by Jones 1979.

Boyne, H. S., and D. J. Fisk. A Laboratory Comparison of Field Techniques for Measurement of the Liquid Water Fraction of Snow, CRREL Report 90-3. Hanover, NH: Cold Regions Research and Engineering Laboratory, 1990.

This report serves as an overview detailing the differences between acid dilution, calorimetric, and dielectric methods. All three methods compare well within a 95 percent confidence interval.

Davis, R. E., and J. Dozier. "Snow Wetness Measurement by Fluorescent Dye Dilution." ***Journal of Glaciology*** **30 (1984): 362–363.**

Describes a novel method for measurement of liquid water content by the addition of Rhodamine WT dye to a snow sample. The liquid water in the sample dilutes the dye and changes the dye concentration. A laboratory fluorimeter is used to measure fluorescent intensity and the intensity is related to dye concentration by a calibration curve. The authors present calculations quantifying the measurement method along with an error analysis.

Davis, R. E., J. Dozier, E. R. LaChapelle, and R. Perla. "Field and Laboratory Measurements of Snow Liquid Water by Dilution." ***Water Resources Research*** **21 (1985): 1415–1420.**

This paper clearly describes the acid dilution technique for measurement of snow liquid water content. An acid solution with a given molar concentration is added to a snow sample and changes in concentration is related to conductivity using a calibration curve. The procedure involves a conductivity meter and the authors recommend a 0.01 M solution of hydrochloric acid (HCl). Errors associated with ice formation in the sample are discussed and quantified.

Fisk, D. “Method of Measuring Liquid Water Mass Fraction of Snow by Alcohol Solution.” *Journal of Glaciology* 32.112 (1986): 538–539.

Describes how the addition of methanol to a calorimeter containing snow can be used to determine liquid water content. The change in calorimeter temperature over a time of six to eight minutes is recorded and an extrapolated graph temperature is related to liquid water content by calibration.

Halliday, I. G. “The Liquid Water Content of Snow Measurement in the Field.” *Journal of Glaciology* 1.7 (1950): 357–361.

This paper provides a historical overview of different methods for determination of snow liquid water content using calorimetry. The overview is useful for gaining an understanding related to how liquid water content was measured in the early 20th century.

Jones, E. B., A. Rango, and S. M. Howell. “Snowpack Liquid Water Determinations Using Freezing Calorimetry.” *Nordic Hydrology* 14.3 (1983): 113–126.

Presents the theory associated with freezing calorimetry and elaborates on the materials and methods required for field determination of liquid water content. Analogous to Jones 1979, a silicone oil was used to change the temperature of the snow sample.

Jones, R. A Comparison of Centrifuge and Freezing Calorimeter Methods for Measuring Free Water in Snow. Washington, DC: U.S. Dep. of Commerce, National Bureau of Standards, 1979.

Describes how centrifuge (rotating) devices can be used to measure liquid water content along with calorimeter devices that change the temperature of the snow sample. Centrifuge devices operate by rotating a snow sample to separate liquid water from the ice framework. The calorimeter utilized a low-viscosity dimethicone fluid (SF-96-5) as a type of silicone oil that changed the temperature of the snow sample.

GPS

Koch, et al. 2014 presents a method for LWC measurement with Global Positioning System (GPS) receivers placed above and below the snowpack. Koch, et al. 2019 later extended this method to determine additional snowpack properties.

Koch, F., P. Henkel, F. Appel, et al. “Retrieval of Snow Water Equivalent, Liquid Water Content, and Snow Height of Dry and Wet Snow by Combining GPS Signal Attenuation and Time Delay.” *Water Resources Research* (2019): 2018WR024431.

GPS antennas situated above and below the snowpack were used to simultaneously measure snow depth, liquid water content, and density. The model identifies an increase in GPS signal attenuation for high levels of liquid water content.

Koch, F., M. Prasch, L. Schmid, J. Schweizer, and W. Mauser. “Measuring Snow Liquid Water Content with Low-Cost GPS Receivers.” *Sensors* 14.11 (2014): 20975–20999.

This paper was the first to demonstrate how liquid water content can be determined using L1-band GPS signals detected by receivers placed above and below the snowpack. A complete model relating attenuation and refraction of electromagnetic wave propagation is presented. The authors identify and test three different variants of the model using snow pit measurements collected using a Denoth meter and Finnish snow fork.

Acoustic

Kinar and Pomeroy 2015 modify a model of sound wave propagation through snow to include the effects of liquid water content using a mixture theory approach.

Kinar, N. J., and J. W. Pomeroy. "SAS2: The System for Acoustic Sensing of Snow." ***Hydrological Processes*** **29.18 (2015): 4032–4050.**

The authors describe an acoustic system used for measurement of snow density, liquid water content, and temperature. Liquid water content is determined using an inverse model that utilizes a mixture theory related to an effective snowpack density. The speed and attenuation of sound waves in snow are used as inputs to the inverse model.

Snow Microstructure

Microscopy and Photography methods utilize cameras and optics to obtain visual representations of snowflakes or snow particles in the snowpack subjected to sintering and metamorphic processes. These visual representations can be analyzed using machine vision algorithms. Particle Size Spectroscopy utilizes the wavelength distribution of light to determine the size of snow particles. Xray and CT Scanning analysis of snow samples utilize computerized tomography (CT) methods to obtain a representation of snow structure, whereas MRI (magnetic resonance imaging) involves strong magnetic fields. Micropenetrometer measurements determine the mechanical properties of snow by resistance of the snowpack to an applied force. Specific Surface Area (SSA) is often measured using optical methods. Satellite Remote Sensing allows for retrieval of snow particle size over large geographic areas.

Microscopy and Photography

Bentley and Humphries were the first photographers of snowflakes in the early 20th century and their work, Bentley and Humphries 1931, shaped public opinion related to snowflake geometry. Seligman 1936 is a classic example of early scientific photography related to snow and snowpack processes. Nakaya 1954 and Libbrecht 2016 provide information on techniques for microphotography of snow, whereas LaChapelle 1977 is a classic reference that is more useful for snowpit observations of snow particles at a field site. Perla 1985 and Perla and Ommanney 1985 provide techniques for microtome thin-section analysis of snow samples and associated machine vision analysis. Gay, et al. 2002 demonstrates processing algorithms to obtain snow particle geometry. Matzl and Schneebeli 2006 indicate how near-infrared (NIR) photography can be used to determine snowpack layering.

Bentley, W. A., and W. J. Humphries. ***Snow Crystals*****. London and New York: McGraw-Hill, 1931.**

The authors of this book established the first repeatable photographic methods for capturing images of snowflakes in the early 20th century. Although glass plate photography is rarely utilized in a modern context, the book provides useful information on how snowflake photography can be accomplished. Since the authors selected snowflakes for artistic photographic capture, this work cannot be considered as indicative of the geometry of all snowflakes.

Gay, M., M. Fily, C. Genthon, M. Frezzotti, H. Oerter, and J.-G. Winther. "Snow Grain-Size Measurements in Antarctica." ***Journal of Glaciology*** **48.163 (2002): 527–535.**

After snow particles are photographed, the authors measure snow particle size by determination of a mean convex radius utilizing machine vision signal processing involving digital filtering and binarization. Changes in snow particle size with respect to depth over the height of snow is related to metamorphic processes.

LaChapelle, E. R. ***Field Guide to Snow Crystals*****. Vancouver, Canada: J. J. Douglas, 1977.**

This book provides a readable overview on how to photograph and examine snow particles at field sites. Also beneficial for researchers who need to examine snow using a portable microscope.

Langlois, A., A. Royer, B. Montpetit, et al. “On the Relationship between Snow Grain Morphology and in-situ Near Infrared Calibrated Reflectance Photographs.” *Cold Regions Science and Technology* 61.1 (2010): 34–42.

Provides an excellent overview of the theory and techniques of using near infrared (NIR) photography to obtain optical estimates of snow particle diameter from the side of snowpits. Comparisons are made with snow particles extracted from the snowpit and photographed using microphotography.

Libbrecht, K. G. *Field Guide to Snowflakes*. Minneapolis: Voyageur Press, 2016.

A book on snowflakes that provides information on the different types of crystals. Contains a chapter on the magnification required for microscopy and describes elements of snowflake photography related to lighting and equipment.

Matzl, M., and M. Schneebeli. “Measuring Specific Surface Area of Snow by Near-Infrared Photography.” *Journal of Glaciology* 52.179 (2006): 558–564.

This paper was the first to establish the basic principles associated with near-infrared (NIR) photography of snowpit walls for layer identification. Camera calibration and interpretation of snowpack stratigraphy is discussed and demonstrated.

Nakaya, U. *Snow Crystals: Natural and Artificial*. Cambridge, MA: Harvard University Press, 1954.

Describes how snow particles can be observed in the field and grown in the laboratory. Also provides information useful for photographing the snow particles.

Perla, R. “Snow in Strong or Weak Temperature Gradients. Part II: Section Plane Analysis.” *Cold Regions Science and Technology* 11 (1985): 181–186.

This paper indicates how photomicrographs of snow samples can be digitized and subjected to stereological analysis using computer techniques. Changes in snow particle morphology are related to the strength of applied temperature gradients.

Perla, R., and C. S. L. Ommanney. “Snow in Strong or Weak Temperature Gradients. Part I: Experiments and Quantitative Observations.” *Cold Regions Science and Technology* 11 (1985): 23–35.

The authors describe an apparatus used to subject snow samples to temperature gradients for studying snow metamorphic changes. Dimethyl phthalate is identified as a chemical that can be added to a snow sample to preserve the structure for microtome thin-section analysis before photography.

Seligman, G. *Snow Structure and Ski Fields: Being an Account of Snow and Ice Forms Met with in Nature, and a Study on Avalanches and Snowcraft*. London: Macmillan, 1936.

Contains an early-20th-century analysis of phenomena associated with snow and serves as an example of photography used to analyze associated environmental phenomena.

Particle Size Spectroscopy

Painter, et al. 2007 showed how contact spectroscopy can be used obtain the optical grain size of snow, whereas Sun and Zhao 2011 used a spectroradiometer positioned at different angles to a snow sample to characterize the effects of grain size on the snow bidirectional polarized reflectance.

Painter, T. H., N. P. Molotch, M. Cassidy, M. Flanner, and K. Steffen. “Contact Spectroscopy for Determination of Stratigraphy of Snow Optical Grain Size.” *Journal of Glaciology* 53 (2007): 121–127.

The authors demonstrate how snow particle size in a snowpit can be related to the wavelength distribution measured using a spectroradiometer probe placed against the snowpit wall. The light source is a halogen-krypton bulb with a peak irradiance wavelength of 0.966 µm. Grain size was related to light absorption by an optical model.

Sun, Z., and Y. Zhao. “The Effects of Grain Size on Bidirectional Polarized Reflectance Factor Measurements of Snow.” *Journal of Quantitative Spectroscopy and Radiative Transfer* 112.14 (2011): 2372–2383.

A spectroradiometer, halogen lamp source and a goniometer were used to obtain the bidirectional polarized reflectance of a snow sample. The goniometer consisted of an assembly allowing for spectroradiometer measurements to be made at angles to the snow surface. The reflectance was related to snow particle size. Snow samples were changed in size by passing the particles through a sieve.

Xray and CT Scanning

Coléou, et al. 2001 used radiation from a synchrotron beamline for computed tomography (CT) of snow samples, whereas Lundy, et al. 2002 utilized a laboratory CT scanner. Heggli, et al. 2009 provides methods for sampling and preservation of snow samples for laboratory CT scan analysis. Heggli, et al. 2011 provides an overview of techniques used for CT scanning of snow. Applications involving CT-scanning of snow for metamorphic analysis are presented by Kaempfer, et al. 2005. Matzl and Schneebeli 2010 relates CT scans of snow to specific surface area (SSA). Pinzer, et al. 2012 used time-lapse micro-CT scans to characterize the temporal evolution of snow sample microstructure in the presence of a temperature gradient, whereas Calonne, et al. 2014 periodically extracted snow samples from a heat exchanger apparatus and used a micro-CT scanner to quantify microstructure. Calonne, et al. 2012 relate permeability to micro-CT measurements of microstructure.

Calonne, N., F. Flin, C. Geindreau, B. Lesaffre, and S. Rolland du Roscoat. “Study of a Temperature Gradient Metamorphism of Snow from 3-D Images: Time Evolution of Microstructures, Physical Properties and Their Associated Anisotropy.” *The Cryosphere* 8.6 (2014): 2255–2274.

This paper reviews how micro-CT scans of snow samples from a cooling apparatus can be used to measure microstructural parameters. A theoretical model relating microstructure to permeability, tortuosity, and thermal conductivity is presented and applied to the micro-CT data. Anisotropy related to variations in snow microstructure is also quantified. This paper can be considered as a companion to the Calonne, et al. 2012 study.

Calonne, N., C. Geindreau, F. Flin, et al. “3-D Image-Based Numerical Computations of Snow Permeability: Links to Specific Surface Area, Density, and Microstructural Anisotropy.” *The Cryosphere* 6.5 (2012): 939–951.

This paper presents a basic theory relating permeability to snow microstructure found using micro-CT scans. Extensive comparisons are made with other measurements reported in the literature.

Coléou, C., B. Lesaffre, J.-B. Brzoska, W. Ludwig, and E. Boller. “Three-Dimensional Snow Images by X-ray Microtomography.” *Annals of Glaciology* 32 (2001): 75–81.

Snow was placed in a rotating sample stage with a volume of 1 cm^3 at a beamline of the European Synchrotron Radiation Facility (ESRF). The sample holder was designed to be refrigerated by liquid nitrogen and circulating nitrogen gas prevented condensation. Diethyl-orthophthalate (phthalate) was used to stabilize the sample. Stereological analysis conducted using computer programs obtained porosity and curvature to characterize snow structure and metamorphism.

Heggli, M., E. Frei, and M. Schneebeli. “Snow Replica Method for Three-Dimensional X-ray Microtomographic Imaging.” *Journal of Glaciology* 55.192 (2009): 631–639.

Indicates how dimethyl phthalate can be used to preserve the structure of a snow sample for micro-CT scanner measurements. Method accuracy and changes in the snow structure is discussed.

Heggli, M., B. Köchle, M. Matzl, et al. “Measuring Snow in 3-D Using X-ray Tomography: Assessment of Visualization Techniques.” *Annals of Glaciology* 52.58 (2011): 231–236.

This paper serves as a comprehensive overview of how to use x-ray techniques to determine the 3D structure of snow samples. The work can serve as a blueprint for planning snow characterization studies using tomographic techniques.

Kaempfer, T. U., M. Schneebeli, and S. A. Sokratov. “A Microstructural Approach to Model Heat Transfer in Snow.” *Geophysical Research Letters* 32.21 (2005): L21503.

Describes how a temperature gradient can be applied across a snow sample placed inside of a micro-CT scanner holder. The paper is important since it was one of the first to relate micro-CT scanner data to a model of heat transport through snow. This allowed for a better understanding of the relationships between snow microstructure and heat transport.

Lundy, C. C., M. Q. Edens, and R. L. Brown. “Measurement of Snow Density and Microstructure Using Computed Microtomography.” *Journal of Glaciology* 48 (2002): 312–316.

Indicates how microstructure is related to snow density using CT-scan images. This paper reported one of the first applications of CT-scan technology for measurement of snow samples.

Matzl, M., and M. Schneebeli. “Stereological Measurement of the Specific Surface Area of Seasonal Snow Types: Comparison to Other Methods, and Implications for mm-Scale Vertical Profiling.” *Cold Regions Science and Technology* 64.1 (2010): 1–8.

Micro-CT scans and microtomed snow samples were used by the authors to obtain stereological parameters. The authors show how the stereological data is related to specific surface area (SSA) of snow samples.

Pinzer, B. R., M. Schneebeli, and T. U. Kaempfer. “Vapor Flux and Recrystallization during Dry Snow Metamorphism under a Steady Temperature Gradient as Observed by Time-Lapse Micro-Tomography.” *The Cryosphere* 6.5 (2012): 1141–1155.

This paper reports the first time-lapse micro-CT scans of snow subjected to a temperature gradient where the visual images are processed by particle image velocimetry (PIV) to quantify the mass flux of vapor transport. Numerical models were used for comparison to gain insight into the physical processes of snow sample metamorphism.

MRI

Ozeki, et al. 2003a establishes the basic techniques of magnetic resonance imaging (MRI) of snow samples, whereas Ozeki, et al. 2003b provides further information on chemicals added to a snow sample for contrast enhancement.

Ozeki, T., K. Kose, T. Haishi, S. Hashimoto, S. Nakatsubo, and K. Nishimura. “Three-Dimensional Snow Images by MR Microscopy.” *Magnetic Resonance Imaging* 21.3–4 (2003a): 351–354.

Snow samples were placed inside of a custom-designed magnetic resonance imaging (MRI) device and 3D images of snow particle structure were obtained. A cooling system was utilized to maintain the snow at a constant temperature. Comparisons are made with section-plane images. The authors found that the snow sample had to be stabilized with iron acetylacetonate, doped aniline, or dodecane to increase MRI signal strength.

Ozeki, T., K. Kose, S. Nakatsubo, K. Nishimura, and A. Hochikubo. “Three-Dimensional MR Microscopy of Snowpack Structures.” *Cold Regions Science and Technology* 37.3 (2003b): 385–391.

An updated version of Ozeki, et al. 2003a, this publication provides a more in-depth analysis of the use of MRI to measure snow structure. The chemical used to stabilize the snow sample is rationalized with respect to the spin-lattice relaxation time.

Micropenetrometer

Proksch, et al. 2015 shows how micropenetrometer measurements indicate changes in snow structure, whereas Havens, et al. 2013 introduces the use of machine learning methods applied to micropenetrometer datasets to identify microstructure differences between snowpack layers.

Havens, S., H. Marshall, C. Pielmeier, and K. Elder. “Automatic Grain Type Classification of Snow Micro Penetrometer Signals with Random Forests.” *IEEE Transactions on Geoscience and Remote Sensing* 51.6 (2013): 3328–3335.

The authors provide an excellent synthesis showing how micropenetrometer measurements can be used to indicate differences in microstructure between snowpack layers. Machine learning techniques are used to relate snow structure data to snow particle type.

Proksch, M., H. Löwe, and M. Schneebeli. “Density, Specific Surface Area, and Correlation Length of Snow Measured by High-Resolution Penetrometry.” *Journal of Geophysical Research: Earth Surface* 120.2 (2015): 346–362.

The paper shows how micropenetrometer measurements indicate differences in snow structure over the height of snow. Snow structural parameters were obtained from penetration force measurements by application of mathematical models. CT scanning of snow (see Xray and CT Scanning section for some papers) was used for comparison.

Specific Surface Area (SSA)

Matzl and Schneebeli 2006 demonstrated how a digital camera with an infrared filter can determine specific surface area (SSA) of snow by an empirical relationship between infrared reflectance and SSA. Gallet, et al. 2009 used an integrating sphere to measure the SSA of a snow sample extracted from the snowpack, whereas Arnaud, et al. 2011 describes a system with a laser and photodiodes situated at different angles to the snow surface. The Arnaud, et al. 2011 system can be used for profiling SSA over the depth of snow using a borehole created in the snowpack.

Arnaud, L., G. Picard, N. Champollion, et al. “Measurement of Vertical Profiles of Snow Specific Surface Area with a 1 cm Resolution Using Infrared Reflectance: Instrument Description and Validation.” *Journal of Glaciology* 57 (2011): 17–29.

Describes a sensor comprised of an optical system with a laser and photodiodes situated at different angles of reflection to the snow surface. The optical system is lowered down a borehole into the snowpack and the laser light is reflected from the sides of the borehole. The hemispherical reflectance is related to the specific surface area (SSA) of snow by an analytical relationship.

Gallet, J.-C., F. Domine, C. S. Zender, and G. Picard. “Measurement of the Specific Surface Area of Snow Using Infrared Reflectance in an Integrating Sphere at 1310 and 1550 nm.” *The Cryosphere* 3.2 (2009): 167–182.

The authors provide a technique to measure SSA where an integrating sphere is placed over a snow sample. Laser diodes illuminate the surface of the snow sample and a photodiode detects the diffused light. Calibration relates signal voltage to the SSA of snow. A 1310 nm laser is used for SSA less than 60 m^2 kg^{-1} and a 1550 nm laser for SSA greater than 60 m^2 kg^{-1}.

Matzl, M., and M. Schneebeli. “Measuring Specific Surface Area of Snow by Near-Infrared Photography.” *Journal of Glaciology* 52.179 (2006): 558–564.

A classic and important paper that demonstrates how digital photography with an infrared filter (Kodak Wratten 87c) can be used to measure specific surface area (SSA) of snow. A picture is taken of a snowpit wall and reflectance is calibrated using targets. The SSA is related to calibrated infrared reflectance using an empirical relationship.

Satellite Remote Sensing

Bourdelles and Fily 1993 and Fily 1997 used Landsat datasets to determine snow grain size, whereas Jin, et al. 2008; Lyapustin, et al. 2009; Painter, et al. 2009; Wiebe, et al. 2013; and Zege, et al. 2011 use Moderate Resolution Imaging Spectroradiometer (MODIS) datasets. Nolin and Dozier 2000 used Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) datasets.

Bourdelles, B., and M. Fily. “Snow Grain-Size Determination from Landsat Imagery over Terre Adélie, Antarctica.” *Annals of Glaciology* 17 (1993): 86–92.

The authors used Landsat Thematic Mapper (TM) data along with an atmospheric transfer and snow-reflectance model to determine snow surface particle size in Antarctica. Infrared channels from the TM sensor was related to snow grain size by a remote sensing model.

Fily, M. “Comparison of in situ and Landsat Thematic Mapper Derived Snow Grain Characteristics in the Alps.” *Remote Sensing of Environment* 59.3 (1997): 452–460.

This paper provides a case study related to how TM data can be used to determine snow grain size at field sites in the Grenoble area of the French Alps. Comparisons were made with ground truth data collected at the sites.

Jin, Z., T. P. Charlock, P. Yang, Y. Xie, and W. Miller. “Snow Optical Properties for Different Particle Shapes with Application to Snow Grain Size Retrieval and MODIS/CERES Radiance Comparison over Antarctica.” *Remote Sensing of Environment* 112.9 (2008): 3563–3581.

The authors present a review that shows how the optical properties of snow are related to snow particle size. These properties are used in an atmosphere-snow radiative transfer model applied to locations in Antarctica. The model is compared with field observations of albedo and reflectance.

Lyapustin, A., M. Tedesco, Y. Wang, T. Aoki, M. Hori, and A. Kokhanovsky. “Retrieval of Snow Grain Size over Greenland from MODIS.” *Remote Sensing of Environment* 113.9 (2009): 1976–1987.

Moderate Resolution Imaging Spectroradiometer (MODIS) measurements were used by the authors to obtain snow grain size. After atmospheric corrections and cloud masking, a snow reflectance model utilizing band ratios was applied. Validation involved the use of snow pit observations of snow particle size and modeling with a snowpack evolution model.

Nolin, A. W., and J. Dozier. “A Hyperspectral Method for Remotely Sensing the Grain Size of Snow.” *Remote Sensing of Environment* 74.2 (2000): 207–216.

A satellite remote-sensing data processing algorithm was developed to determine snow particle size and the algorithm outputs were compared with ground-truth spectrometer data. The algorithm is conceptually simple and easily calculated from absorption bands.

Painter, T. H., K. Rittger, C. McKenzie, P. Slaughter, R. E. Davis, and J. Dozier. "Retrieval of Subpixel Snow Covered Area, Grain Size, and Albedo from MODIS." *Remote Sensing of Environment* 113.4 (2009): 868–879.

This paper shows how snow particle size can be determined using a spectral mixture analysis associated with the solution of a linear system of equations. The algorithm was extensively validated at sites in North America and the Himalayas.

Wiebe, H., G. Heygster, E. Zege, T. Aoki, and M. Hori. "Snow Grain Size Retrieval SGSP from Optical Satellite Data: Validation with Ground Measurements and Detection of Snow Fall Events." *Remote Sensing of Environment* 128 (2013): 11–20.

Shows how Moderate Imaging Spectrometer (MODIS) data can be used to obtain snow particle size at sites in the Arctic, Antarctic, Greenland, and Japan. Validation involved a comparison of remote sensing estimates with data collected from snowpits at the sites. The authors demonstrate how remote sensing snow particle size estimates can be related to snow events since the snow grain size is strongly associated with metamorphic processes that occur after snowfall.

Zege, E. P., I. L. Katsev, A. V. Malinka, A. S. Prikhach, G. Heygster, and H. Wiebe. "Algorithm for Retrieval of the Effective Snow Grain Size and Pollution Amount from Satellite Measurements." *Remote Sensing of Environment* 115.10 (2011): 2674–2685.

Building on previous work presented by Wiebe, et al. 2013, a model of optical transmission and reflection is described that can also determine the amount of soot particles present on the snow surface. Model computations and calculations are described along with a flowchart. The importance of atmospheric correction for algorithm application using MODIS data is clearly described.

Snow-Covered Area

Photogrammetry utilizes visual methods to obtain the area of snow with cameras situated on or near the ground surface. UAV Photogrammetry applications involve unmanned aerial vehicles where cameras and Structure-from-Motion (SfM) algorithms are used to obtain the area of snow on the ground. Satellite Remote Sensing utilizes image sensors on remote sensing platforms to obtain snow-covered area over large regions.

Photogrammetry

The basic theory and techniques of photogrammetry for determining Snow Covered Area (SCA) is discussed by Cline 1993 and Cline 1994. Parajka, et al. 2012 is a case study showing how ground-based cameras are deployed. Härer, et al. 2013 clearly describes the algorithms used to obtain snow-covered area from camera images. Pomeroy and Schmidt 1993 demonstrate how photographs of intercepted snow on tree branches can be used to obtain fractal scaling relationships.

Cline, D. W. Measuring Alpine Snow Depths by Digital Photogrammetry. Part 1. Conjugate Point Identification. *Proceedings of the Western Snow Conference* 61 (1993): 265–271.

Provides a complete overview of the machine vision processing related to how airplane photogrammetry can be used to determine snow depth from stereophotographs. This paper can be considered as a companion to the Cline 1994 paper.

Cline, D. W. "Digital Photogrammetric Determination of Alpine Snowpack Distribution for Hydrologic Modelling." *Proceedings of the Western Snow Conference* 62 (1994): 115–123.

This publication provides an in-depth discussion of the geometry and errors associated with photogrammetry. The author identifies effects associated with topographic relief and aerotriangulation to obtain the orientation of the camera relative to the ground surface.

Härer, S., M. Bernhardt, J. G. Corripio, and K. Schulz. "PRACTISE – Photo Rectification And ClassificaTIon SoftwarE (V.1.0)." *Geoscientific Model Development* 6.3 (2013): 837–848.

Describes algorithms to obtain snow-covered area from conventional camera images of a landscape or images derived from remote sensing satellite sensors. The algorithms are clearly described for replication independent of the Matlab code provided in an associated software library and this paper is therefore a good starting point for understanding how snow-covered area (SCA) can be determined using machine vision computer processing.

Parajka, J., P. Haas, R. Kirnbauer, J. Jansa, and G. Blöschl. "Potential of Time-Lapse Photography of Snow for Hydrological Purposes at the Small Catchment Scale." *Hydrological Processes* 26.22 (2012): 3327–3337.

Shows how time-lapse camera images can be used to measure patterns of snow accumulation over distances ranging from 100 m to 300 m and from 1 km to 2 km. A case study in the Austrian Alps details how snow depth markers in the image can be utilized to determine snow depth using a machine vision algorithm.

Pomeroy, J. W., and R. A. Schmidt. "The Use of Fractal Geometry in Modelling Intercepted Snow Accumulation and Sublimation." *Proceedings of the Eastern Snow Conference* 50 (1993): 1–10.

Snow-covered branches at a field site were photographed in front of a black background to determine intercepted snow perimeter-area relationships to quantify sublimation of intercepted snow in branches using fractal mathematics.

UAV Photogrammetry

De Michele, et al. 2016 maps the spatial distribution of snow in alpine terrain using unmanned aerial vehicles (UAVs), whereas Harder, et al. 2016 quantifies ablation rates and the spatial distribution of snowcover in prairie and alpine environments.

De Michele, C., F. Avanzi, D. Passoni, et al. "Using a Fixed-Wing UAS to Map Snow Depth Distribution: An Evaluation at Peak Accumulation." *The Cryosphere* 10.2 (2016): 511–522.

A SenseFly UAV with a digital camera was used to capture images of a catchment in the Italian Alps. Processing utilized a Structure from Motion (SfM) software algorithm that allowed for production of a Digital Surface Model (DSM) indicative of snow-covered area.

Harder, P., M. Schirmer, J. Pomeroy, and W. Helgason. "Accuracy of Snow Depth Estimation in Mountain and Prairie Environments by an Unmanned Aerial Vehicle." *The Cryosphere* 10.6 (2016): 2559–2571.

A UAV (SenseFly Ebee) deployed at mountain and prairie locations was used to obtain a digital surface model (DSM) suitable for determination of Snow-Covered Area (SCA). Structure from Motion (SfM) software algorithms were also used for this application.

Satellite Remote Sensing

Theory and modeling related to satellite-based active radar sensors for Snow Covered Area (SCA) estimation is provided by Luojus, et al. 2007. Armstrong and Brodzik 2001 indicates how SCA can be derived using passive satellite remote-sensing products at global scales, whereas Frei and Lee 2010 demonstrates how SCA is obtained on a continental scale and Brown, et al. 2010 shows how SCA is determined in the Arctic. Maurer, et al. 2003 and Boudhar, et al. 2010 show how passive satellite sensors can obtain SCA in snow-covered basins at a regional scale. Hall, et al. 2010 quantifies SCA uncertainty related to cloud cover. Painter, et al. 2009 shows how spectral mixture analysis can determine SCA and incorporate effects of topographic shading into the remote sensing model. Bormann, et al. 2018 reviews satellite technologies for measurement of changes in SCA, indicating the need for future missions and sensors to measure snowpack variability, particularly in regions such as Arctic and Alpine environments sensitive to climate change.

Armstrong, R. L., and M. J. Brodzik. “Recent Northern Hemisphere Snow Extent: A Comparison of Data Derived from Visible and Microwave Satellite Sensors.” *Geophysical Research Letters* 28.19 (2001): 3673–3676.

The authors compare visible and passive microwave remote-sensing data products to determine SCA over the Northern Hemisphere. Trends and errors are discussed in a geographic context. The best agreement between visible and passive microwave datasets was found to occur during January and February since errors associated with passive microwave measurements are higher during times of patchy and thin snowcover.

Bormann, K. J., R. D. Brown, C. Derksen, and T. H. Painter. “Estimating Snow-Cover Trends from Space.” *Nature Climate Change* 8.11 (2018): 924–928.

This paper is an excellent overview of the spatial scale of remote sensing satellite data for measurement of SCA. Declines in snow cover are identified along with regional changes. This paper is useful as a pedagogical introduction to SCA remote sensing and snow extent depletion.

Boudhar, A., B. Duchemin, L. Hanich, et al. “Long-Term Analysis of Snow-Covered Area in the Moroccan High-Atlas through Remote Sensing.” *International Journal of Applied Earth Observation and Geoinformation* 12 (2010): S109–S115.

This paper shows how SPOT-4 and SPOT-5 satellite VEGETATION sensor spectral bands can be used to determine SCA in the mountains of Morocco. Measurements of SCA over this region were used to examine correlations with Northern Atlantic sea level pressure datasets.

Brown, R., C. Derksen, and L. Wang. “A Multi-Data Set Analysis of Variability and Change in Arctic Spring Snow Cover Extent, 1967–2008.” *Journal of Geophysical Research: Atmospheres* 115.D16 (2010).

Indicates how Arctic snow cover distribution can be obtained by combining ten remote sensing datasets from different temporal periods. Errors, biases and spatial correlations in the resulting dataset are discussed.

Frei, A., and S. Lee. “A Comparison of Optical-Band Based Snow Extent Products during Spring over North America.” *Remote Sensing of Environment* 114.9 (2010): 1940–1948.

This paper shows differences between two raster data products for determining snow cover distribution on a continental scale. Contains a readable discussion that addresses effects of cloud cover and spatial inaccuracies.

Hall, D. K., G. A. Riggs, J. L. Foster, and S. V. Kumar. “Development and Evaluation of a Cloud-Gap-Filled MODIS Daily Snow-Cover Product.” *Remote Sensing of Environment* 114.3: (2010): 496–503.

Moderate Resolution Imaging Spectroradiometer (MODIS) data was used to determine SCA with a robust algorithm that compensates for the presence of clouds. To quantify uncertainty related to cloud cover, the resulting data products include a raster dataset of cloud-persistence count (CPC) that indicates the age of the snow surface observation used for determining SCA.

Luojus, K. P., J. T. Pulliainen, S. J. Metsamaki, and M. T. Hallikainen. “Snow-Covered Area Estimation Using Satellite Radar Wide-Swath Images.” *IEEE Transactions on Geoscience and Remote Sensing* 45.4 (2007): 978–989.

This paper was the first to use Radarsat C-band SAR data to measure SCA for environments ranging from open to forested areas in northern Finland. A complete theory of radar backscattering from snow is presented along with an error analysis. SCA determined from visible satellite imagery was used for comparison.

Maurer, E. P., J. D. Rhoads, R. O. Dubayah, and D. P. Lettenmaier. “Evaluation of the Snow-Covered Area Data Product from MODIS.” *Hydrological Processes* 17.1 (2003): 59–71.

Data from the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to obtain SCA of the Columbia River and Missouri River basins. Raster datasets from MODIS were compared with National Operational Hydrologic Remote Sensing Center (NOHRSC) datasets and field site observations showing the influences of cloud cover, forested area, and complex topography.

Painter, T. H., K. Rittger, C. McKenzie, P. Slaughter, R. E. Davis, and J. Dozier. “Retrieval of Subpixel Snow Covered Area, Grain Size, and Albedo from MODIS.” *Remote Sensing of Environment* 113.4 (2009): 868–879.

The paper shows how a constrained spectral mixture analysis model can be used to robustly obtain SCA from MODIS data. Each remote sensing pixel is composed of a fractional land cover. The model also compensates for topographic shading.

Blowing Snow

Mechanical Traps are collection devices for blowing snow particles during wind redistribution events. Optical devices utilize light extinction coefficients or camera systems to quantify blowing snow processes. Acoustic devices involve the detection of pressure waves created by snow particle interactions with a structure. Remote Sensing involves satellite or near-surface sensors used to observe blowing snow.

Mechanical Traps

Mellor 1960 describes the design and testing of the first “rocket-type” traps to collect blowing snow. Jairell 1975 and Fohn 1980 introduce engineering updates to the Mellor 1960 trap and indicate how this type of trap can be efficiently deployed at field sites. Schmidt, et al. 1984 compares filter-fabric bag traps with the “rocket-type” traps. A more recent mechanical trap is described by Bolognesi 1995 as a series of collection devices oriented to trap snow in different directions.

Bolognesi, R. “The Driftometer.” *Proceedings: 1995 International Snow Science Workshop* (1995): 144–148.

This paper describes the theory and design of a snow particle collection device that traps drifting snow in the saltation layer above the snow surface. The collection of snow particles in different directions is accomplished by deployment of separate devices on a vertical post. The authors demonstrate how data from the collection device can be utilized for calculation of an avalanche activity index.

Fohn, P. M. B. “Snow Transport over Mountain Crests.” *Journal of Glaciology* 26.94 (1980): 469–480.

Shows how the “rocket-type” shape of the Mellor 1960 blowing snow trap can be modified to ensure an adequate flow efficiency ratio while allowing a transparent section to be elongated to visually determine the presence of particles in the traps. The traps described in this paper were used to measure the mass flux of blowing snow to validate the physics related to a model of snow transport over a ridge.

Jairell, R. L. “An Improved Recording Gage for Blowing Snow.” *Water Resources Research* 11.5 (1975): 674–680.

The “rocket-type” trap of Mellor 1960 was modified by the authors to measure the mass flux of blowing snow over a larger volume of air. The trap is placed on a turntable assembly to allow snow particles to be sampled in the dominant wind direction. A disadvantage of the device can be prior preparation required for installation at a field site since a pit needs to be created to house the mechanical assembly.

Mellor, M. “Gauging Antarctic Drift Snow.” Paper presented at a the symposium held in Melbourne, February 1959. In *Antarctic Meteorology*. 347–354. Oxford: Pergamon Press, 1960.

This reference describes the first blowing snow traps used to measure the mass flux of blowing snow in Antarctica. Design considerations of the traps are presented. This document is one of the first to describe the "rocket type" blowing snow trap and provides historical insight related to the measurement and analysis of blowing snow.

Schmidt, R. A., R. Meister, and H. Gubler. "Comparison of Snow Drifting Measurements at an Alpine Ridge Crest." ***Cold Regions Science and Technology*** **9.2 (1984): 131–141.**

Describes the use of sock traps with a filter-fabric bag and "rocket type" traps to measure the mass flux of blowing snow at a ridge site in the Swiss Alps. The dimensions of two different sizes of sock traps with 0.105 mm fabric meshes are provided: a smaller trap with orifice dimensions of 3 mm by 25 mm, and a larger trap with orifice dimensions of 2 cm by 15 cm.

Optical

The authors of Sommerfeld and Businger 1965 were the first to utilize an incandescent light bulb, optical assembly, and two photoresistors to determine the mass flux of blowing snow, whereas Schmidt and Sommerfeld 1969 introduced a similar system with two phototransistors. Particle counters utilizing light-emitting diodes (LEDs) and a single photodetector are described by Gubler 1981 and Brown and Pomeroy 1989, whereas Sato, et al 1993 used a laser diode, dual photodiode, and an associated processing system with a microcontroller. Schmidt, et al. 1984 compares Optical and Mechanical Traps. Gordon and Taylor 2009 and Gordon, et al. 2009 utilized conventional video camera systems and light sources to measure blowing snow, whereas Aksamit and Pomeroy 2016 utilized a high-speed camera and a laser.

Aksamit, N. O., and J. W. Pomeroy. "Near-Surface Snow Particle Dynamics from Particle Tracking Velocimetry and Turbulence Measurements during Alpine Blowing Snow Storms." ***The Cryosphere*** **10.6 (2016): 3043–3062.**

Indicates how a high-speed camera and a laser can be used for particle tracking velocimetry (PTV) of blowing snow to measure velocity vectors and particle fluxes. The authors were able to quantify turbulence and snow particle dynamics.

Brown, T., and J. W. Pomeroy. "A Blowing Snow Particle Detector." ***Cold Regions Science and Technology*** **16.2 (1989): 167–174.**

Describes the design of the first optical blowing snow instrumentation device to use a fiber optic cable attached to a photodiode situated at an offset distance to an infrared LED. Blowing snow particles passing between the LED and photodiode reduce the light transmittance. Mie scattering theory and empirical relationships are utilized to determine the mass flux of blowing snow.

Gordon, M., S. Savelyev, and P. A. Taylor. "Measurements of Blowing Snow, Part II: Mass and Number Density Profiles and Saltation Height at Franklin Bay, NWT, Canada." ***Cold Regions Science and Technology*** **55.1 (2009): 75–85.**

This paper describes a companion camera system to the Gordon and Taylor 2009 paper that operates by using reflected light from snow particles passing in front of the lens. A black background placed 15 cm from the camera and lens enclosure allowed for image binarization and machine vision analysis.

Gordon, M., and P. A. Taylor. "Measurements of Blowing Snow, Part I: Particle Shape, Size Distribution, Velocity, and Number Flux at Churchill, Manitoba, Canada." ***Cold Regions Science and Technology*** **55.1 (2009): 63–74.**

The authors introduce a custom camera and lens system used to measure blowing snow. A 640 × 512 pixel image sensor is coupled to a lens. The lens and image sensor are situated at an offset distance to a halogen lamp that serves to illuminate snow particles. The particle distribution, size, and velocity were used to determine the mass flux of blowing snow.

Gubler, H. "An Electronic Remote Snow-Drift Gauge." ***Journal of Glaciology*** **27 (1981): 164–174.**

Describes a system comprised of a collimated LED and a photodiode situated at an offset distance to the LED. Snow particles pass through a sensing volume and the field of view is limited by a slit. The authors indicate that the system was designed to transmit data using a radio communication link.

Sato, T., T. Kimura, T. Ishimaru, and T. Maruyama. "Field Test of a New Snow-Particle Counter (SPC) System." *Annals of Glaciology* 18 (1993): 149–154.

Describes a system with a laser diode and a dual photodiode coupled to a dual-slit assembly. Snow particles passing through the sensing volume successively interrupt the light passing through each of the slits and create two pulses. A microcontroller computes the mass flux using the peak voltage of the pulses and the time between pulses.

Schmidt, R. A., R. Meister, and H. Gubler. "Comparison of Snow Drifting Measurements at an Alpine Ridge Crest." *Cold Regions Science and Technology* 9.2 (1984): 131–141.

An experimental setup comprised of snow particle counters, computers, and analog-to-digital converters were deployed along with mechanical traps at a field site in the Swiss Alps. Comparisons were made between the devices. This paper serves as a classic example of automation at environmental measurement field sites in the 1980s before commercial dataloggers and associated equipment displaced custom-designed electronics.

Schmidt, R. A., and R. A. Sommerfeld. "A Photoelectic Snow Particle Counter." *Proceedings of the Western Snow Conference* 37 (1969): 88–91.

Describes an early system for measurement of the mass flux of blowing snow utilizing an incandescent light bulb and two phototransistors.

Sommerfeld, R., and J. A. Businger. "The Density Profile of Blown Snow." *Journal of Geophysical Research* 70.14 (1965): 3303–3306.

The authors describe a novel device involving an incandescent light bulb, two photoresistors, a mirror, and prism to measure the mass flux of blowing snow over a 1.5 m distance. Calibration of the voltage difference output from a bridge circuit was used to determine the mass flux of blowing snow.

Acoustic

Chritin, et al. 1999 introduced the use of a vertical pipe to measure blowing snow as the "FlowCapt" sensor. Wind-transported snow particles interact with the pipe and create sound waves that are sensed by an acoustic transducer inside of the pipe. Calibration theory for the FlowCapt is provided by Michaeux, et al. 2000; Jaedicke 2001; and Cierco, et al. 2007. The Jaedicke 2001 and Cierco, et al. 2007 papers describe a segmented version of the device suitable for measuring the mass flux of blowing snow at different heights above the ground surface. Font, et al. 1998 describes field testing of the FlowCapt device and associated comparisons with Optical sensors and Mechanical Traps. Tüg 1988 describes a device where snow particles directly interact with a piezoelectric sensor in lieu of a pipe.

Chritin, V., R. Bolognesi, and H. Gubler. "FlowCapt: A New Acoustic Sensor to Measure Snowdrift and Wind Velocity for Avalanche Forecasting." *Cold Regions Science and Technology* 30.1–3 (1999): 125–133.

The authors describe a device consisting of a vertical pipe deployed at a field site. Transducers inside the pipe detect sound waves created when blowing snow particles interact with the pipe. A digitized signal of the sound waves is related to blowing snow mass flux by empirical calibration.

Cierco, F.-X., F. Naaim-Bouvet, and H. Bellot. “Acoustic Sensors for Snowdrift Measurements: How Should They Be Used for Research Purposes?” *Cold Regions Science and Technology* 49.1 (2007): 74–87.

This paper provides a study comparing a FlowCapt sensor to mechanical trap measurements of blowing snow mass flux. Calibration equations for the FlowCapt sensor are provided based on wind tunnel and laboratory measurements that quantify the effect of particle velocity on the detected signal. The paper describes a multi-segmented version of the device that measures the mass flux of blowing snow at different heights above the ground.

Font, D., F. Naaim-Bouvet, and M. Roussel. Drifting-Snow Acoustic Detector: Experimental Tests in La Molina, Spanish Pyrenees. *Annals of Glaciology* 26 (1998): 221–224.

Describes a field comparison test of the FlowCapt instrument involving data collected using optical gauges and mechanical traps at a site in the eastern Pyrenees of Spain.

Jaedicke, C. “Acoustic Snowdrift Measurements: Experiences from the FlowCapt Instrument.” *Cold Regions Science and Technology* 32.1 (2001): 71–81.

Provides a further description of the FlowCapt instrument with a diagram clearly showing how a multi-segmented device can be used to quantify mass flux as a function of distance above the snow surface. Demonstrates how data can be collected using three FlowCapt measurement devices situated across a valley to quantify the mass flux of blowing snow from a valley to a fjord on the island of Spitsbergen, Norway.

Michaeux, J. L., F. Naaim-Bouvet, M. Naaim, and G. Guyomarc’h. “The Acoustic Snowdrift Sensor: Interests, Calibration and Results.” *Proceedings of the 2000 International Snow Science Workshop* (2000): 390–395.

Provides an overview of how the FlowCapt sensor is calibrated using data collected in a wind tunnel and at a field site. Describes relationships between snow particle type and signal strength, indicating that snow depth around the sensor can influence the detected signal.

Tüg, H. “A Pulse-Counting Technique for the Measurement of Drifting Snow.” *Annals of Glaciology* 11 (1988): 184–186.

The author describes a novel sensor consisting of a device with a fin that rotates in a similar fashion to a wind direction sensor. Snow particles transported by the wind interact with a piezoelectric sensor situated at the end of the sensor body. Particle counts are related to the mass flux of blowing snow by calibration.

Remote Sensing

Gossart, et al. 2017 shows how a ground-based LIDAR device can be used along with a suitable processing algorithm for detection of blowing snow events at an Antarctic field site, whereas Palm, et al. 2011 uses satellite LIDAR to detect these events over large areas of Antarctica. Passive remote sensing satellite algorithms are described by Frezzotti, et al. 2002 and Scarchilli, et al. 2010.

Frezzotti, M., S. Gandolfi, F. L. Marca, and S. Urbini. “Snow Dunes and Glazed Surfaces in Antarctica: New Field and Remote-Sensing Data.” *Annals of Glaciology* 34 (2002): 81–88.

Landsat remote sensing datasets and ground-truth data along transects showed dunes and macro-relief features at Antarctic field sites. The authors demonstrate how the surface variability is related to wind direction and blowing snow events.

Gossart, A., N. Souverijns, I. V. Gorodetskaya, et al. "Blowing Snow Detection from Ground-Based Ceilometers: Application to East Antarctica." ***The Cryosphere*** **11.6 (2017): 2755–2772.**

Ceilometers are normally used to detect cloud height by laser backscatter. The authors of this paper present an algorithm to detect blowing snow events using attenuation indicated by the backscattered signal. Tests conducted using data collected from stations at East Antarctica showed that the algorithm was able to detect the presence of blowing snow with a 78 percent accuracy compared to ground-based observations.

Palm, S. P., Y. Yang, J. D. Spinhirne, and A. Marshak. "Satellite Remote Sensing of Blowing Snow Properties over Antarctica." ***Journal of Geophysical Research*** **116.D16 (2011).**

The authors provide a technique for detection of blowing snow events using satellite LIDAR. Signal processing is utilized to detect the location of the snow surface. Blowing snow is detected by the signal processing algorithm above the snow surface if the windspeed is greater than a threshold value and the backscattered signal is above a threshold indicative of blowing snow.

Scarchilli, C., M. Frezzotti, P. Grigioni, L. De Silvestri, L. Agnoletto, and S. Dolci. "Extraordinary Blowing Snow Transport Events in East Antarctica." ***Climate Dynamics*** **34.7 (2010): 1195–1206.**

The frequency of blowing snow events is measured using MODIS TERRA images that indicate snow surface features and dunes indicative of transport. The use of models and measurements from ground and satellite observations allowed the authors to quantitatively estimate snow transport mass fluxes.

Temperature and Thermal Properties

Thermistors and Thermocouples are devices used to measure snowpack temperature that are either inserted into the snowpack or placed on a structure to measure temperature within an accumulated mass of snow. Heat Pulse Probes measure the thermal properties of a snowpack and consist of heater needles inserted into the snow. Changes in temperature at a heater needle or at an offset distance to the needle are used to determine thermal conductivity or diffusivity; these quantities are important for measuring heat transport through snow to assess the rate of snowpack evolution and associated metamorphic processes. Self-Contained Sensor Systems involve the use of iButton dataloggers or small digital temperature sensors to measure snow temperature and snowpack processes. The iButton is a small sensing system with an onboard battery and memory that can autonomously log temperature over a time period of months. Temperature time series are transferred to a computer using an iButton reader device that needs an electrical connection to the iButton. Optical Temperature Sensing utilizes lasers to measure snowpack temperature via scintillometer physics or fiber optic cables. Infrared Photography and IR Sensors measure snow temperature using a photodetector assembly and application of the Stefan-Boltzmann Law.

Thermistors and Thermocouples

Gerdel 1944 was one of the earliest studies to report the use of thermistors and thermocouples arranged along horizontal wires in a "trellis" structure to measure the temperature of an accumulated snowpack. A similar structure was used by Luce and Tarboton 2001. Helgason and Pomeroy 2012 used a frame with thermocouples on vertical wires situated throughout the snowpack to obtain a spatial distribution of snow temperature over the height of snow. Sturm and Johnson 1991 deployed thermistors on a three-dimensional grid and showed the existence of convection plumes occurring throughout the snowpack. Albert and McGilvary 1991 did not use a supporting frame and placed thermocouples on the ground and snow surface. Progressive snowfall events buried the thermocouples in the snowpack. All these temperature measurement techniques are influenced by solar heating along supporting wires and thereby require data to be constrained or removed from a time series dataset when temperature measurement sensors are exposed above the snowpack during the snow accumulation or ablation season.

Albert, M. R., and W. R. McGilvary. "Multidimensional Observation of Snow Temperature on Windy Days." ***Proceedings of the Eastern Snow Conference*** **48 (1991): 189–200.**

This paper demonstrates how an array of thermocouples in the snowpack can be situated at different heights without the use of a supporting frame. Before the snow accumulation season, the authors arranged a 5 by 5 array of thermocouples with a 10 cm grid spacing on a sand ground surface for a total of 25 thermocouples per layer. After 12 cm of snow accumulation, another grid of thermocouples was placed on the snow surface. This second layer of thermocouples was progressively covered by snow.

Gerdel, R. W. "Snow-Temperature Studies and Apparatus at the Soda Springs, California, Cooperative Snow-Research Project." ***Eos, Transactions American Geophysical Union*** **25.1 (1944): 118–122.**

This early study reviewed the use of electronic temperature sensing devices to measure the snowpack, indicating that thermocouples had been used as early as 1920. At Soda Springs, California, the author installed a "trellis" consisting of thermocouples and thermistors placed along metal wires situated horizontally between wooden posts.

Helgason, W., and J. Pomeroy. "Problems Closing the Energy Balance over a Homogeneous Snow Cover during Midwinter." ***Journal of Hydrometeorology*** **13.2 (2012): 557–572.**

The authors describe a frame comprised of thermocouples situated along wires oriented vertically over the height of a copper frame. The frame was painted white to reduce solar heating. The installation was limited to five thermocouples per wire to reduce effects associated with thermocouples influencing the thermal properties of the snowpack.

Luce, C. H., and D. G. Tarboton. "A Modified Force-Restore Approach to Modelling Snow-Surface Heat Fluxes." ***Proceedings of the Western Snow Conference*** **69 (2001): 103–114.**

Thermocouples were placed along a vertical "ladder" at various heights above the ground surface to measure snow temperature. Analogous to the experimental setup utilized for other studies, snow accumulated around the structure. The data was used to validate a model of heat transport through the snowpack.

Sturm, M., and J. B. Johnson. "Natural Convection in the Subarctic Snow Cover." ***Journal of Geophysical Research*** **96 (1991): 11657–11671.**

This study is important since it was the first to demonstrate that convection plumes occur inside a snowpack due to heat and mass transport. Thermistors were placed on a three-dimensional grid throughout the snowpack utilizing five vertical and six horizontal wires. Three-dimensional plots of temperature estimated the flow velocity associated with convection plumes.

Heat Pulse Probes

Sturm, et al. 1997 provides historical context for heat pulse probe measurements and a widely used empirical relationship relating snow density to thermal conductivity. Sturm, et al. 1997 used a single-probe device to collect numerous measurements. Sturm, et al. 2002 relates thermal conductivity measurements collected using a single-probe device to snowpack metamorphism. Liu and Si 2008 used a dual-probe device to measure snow density and thermal conductivity. Morin, et al. 2010 demonstrates how heat pulse probes can be placed into a structure to measure snowpack thermal properties over the height of the snowpack.

Liu, G., and B. C. Si. Dual-Probe Heat Pulse Method for Snow Density and Thermal Properties Measurement. ***Geophysical Research Letters*** **35 (2008): 1–5.**

This paper was the first to utilize a dual-probe heat pulse probe to measure snow density. The authors found that a 60 s heat pulse with a strength less than 15 W m^{-1} and a temperature rise of less than 0.5 K was suitable for reducing thermal changes in the snow sample during the time of measurement. Dual-probe measurements tended to overestimate snow density.

Morin, S., F. Domine, L. Arnaud, and G. Picard. “In-situ Monitoring of the Time Evolution of the Effective Thermal Conductivity of Snow.” *Cold Regions Science and Technology* 64.2 (2010): 73–80.

Single heat pulse probes were placed into a structure that situated the probes at different heights above the ground surface. The thermal conductivity of the snow that accumulated around the structure was measured by heating and cooling of each probe. The authors were the first to address the influence of probe thermal contact and analyze possible effects associated with the probe heat influencing snowpack temperature and metamorphism.

Sturm, M., J. Holmgren, M. König, and K. Morris. “The Thermal Conductivity of Seasonal Snow.” *Journal of Glaciology* 43 (1997): 26–41.

This paper provides a good historical overview of snow thermal conductivity measurements, demonstrating that experiments involving heat pulses have been conducted since the late 1800s. The authors use existing datasets and hundreds of data points collected using a single heat pulse probe to determine an empirical relationship between snow thermal conductivity and snow density. The relationships given in this paper has been widely used for snowpack modeling.

Sturm, M., D. K. Perovich, and J. Holmgren. “Thermal Conductivity and Heat Transfer through the Snow on the Ice of the Beaufort Sea.” *Journal of Geophysical Research-Oceans* 107 (2002): 8043.

The authors measured the thermal conductivity along a transect situated across the ice of the Beaufort Sea using a single probe device. Changes in thermal conductivity along the transect were related to metamorphic changes, snow crystal type, and processes of snowpack evolution associated with heat transport.

Self-Contained Sensor Systems

Lewkowicz 2008 and Reusser and Zehe 2011 use iButtons placed on a vertical pole to measure snow temperatures over the height of snow whereas Léger, et al. 2019 describes a similar system utilizing 1-wire temperature sensors interfaced to a single board computer. Lundquist and Lott 2008 deployed iButtons to measure temperatures at the snow-soil interface whereas Lundquist and Rochford 2007 placed iButtons in small radiation shields to characterize the spatial distribution of temperatures across a watershed.

Léger, E., B. Dafflon, Y. Robert, et al. “A Distributed Temperature Profiling Method for Assessing Spatial Variability in Ground Temperatures in a Discontinuous Permafrost Region of Alaska.” *The Cryosphere* 13.11 (2019): 2853–2867.

The authors describe a temperature sensing system comprised of digital 1-Wire thermometers situated on a vertical pole and electrically connected to a Raspberry Pi single board computer. The probes were placed along a transect and used to obtain spatially dense measurements of ground temperatures related to permafrost and snowpack distribution. Although the authors collected data during the summer months, the paper indicates how the system might be utilized for snow measurement.

Lewkowicz, A. G. “Evaluation of Miniature Temperature-Loggers to Monitor Snowpack Evolution at Mountain Permafrost Sites, Northwestern Canada.” *Permafrost and Periglacial Processes* 19.3 (2008): 323–331.

This paper contains a case study showing how self-contained iButton temperature loggers can be placed at different heights above the ground surface on a vertical pole to measure changes in temperature throughout snow that accumulates around the pole. A difficulty of using the iButtons is that the data from each small (17.35 mm diameter) logger had to be individually downloaded.

Lundquist, J. D., and F. Lott. “Using Inexpensive Temperature Sensors to Monitor the Duration and Heterogeneity of Snow-Covered Areas.” *Water Resources Research* 44.4 (2008).

The paper demonstrates how iButton sensors can be placed in plastic wrap for deployment to measure snow accumulation and ablation. Situated in and near the snow-soil interface, the iButtons determined spatial differences in temperature related to snow accumulation.

Lundquist, J., and C. Rochford. “Distributed Temperatures in the Snow Zone: Spatial Patterns and Innovative Measurement Techniques.” *Proceedings of the Western Snow Conference* 75 (2007): 43–51.

The authors describe how self-recording iButton temperature sensors can be deployed in a novel fashion to obtain areal measurement of environmental temperatures in the Sierra Nevada (Yosemite National Park, United States). The iButtons were placed in small radiation shields placed on poles and in trees.

Reusser, D. E., and E. Zehe. “Low-Cost Monitoring of Snow Height and Thermal Properties with Inexpensive Temperature Sensors.” *Hydrological Processes* 25.12 (2011): 1841–1852.

Demonstrates how iButtons situated along a vertical post can estimate snow depth as the height of snow in conjunction with a temperature index model. The cold content as the amount of energy required to be added to the snowpack to raise the temperature to the melting point (0 °C) was also computed using the iButton data.

Optical Temperature Sensing

Tyler, et al. 2008 installed a distributed temperature sensing (DTS) system on the ground surface before the snow accumulation season and measured changes in temperature underneath the snowpack.

Tyler, S. W., S. A. Burak, J. P. McNamara, A. Lamontagne, J. S. Selker, and J. Dozier. Spatially Distributed Temperatures at the Base of Two Mountain Snowpacks Measured with Fiber-Optic Sensors. *Journal of Glaciology* 54.187 (2008): 673–679.

Describes a study that utilized distributed temperature sensing (DTS) to measure temperatures at the snow-soil interface. A 300 m fiber-optic cable was placed on the ground surface before snow accumulation to measure temperature by Raman scattering. Changes in temperature were related to solar radiation, air temperature, and snowmelt processes.

Infrared Photography and IR Sensors

Shea and Jamieson 2011 establishes theory and practical considerations associated with the use of infrared (IR) thermal imagers to examine heat transport processes within the snowpack. Shea, et al. 2012 demonstrates how thermal imagers show sub-surface heating of the snowpack and solar warming of a snow surface crust. Schirmer and Jamieson 2014 indicates why thermal imaging of snow is challenging and caution that snow pit measurements with these imagers do not always accurately represent thermal gradients occurring within the snowpack. Pomeroy, et al. 2006 uses a thermal imager to quantify radiative transfer between shrubs and the snowpack during ablation. Lundquist, et al. 2018 provides a technique for separating vegetation and snow temperatures using data collected from thermal imagers situated on aircraft. Rees 1993 is a classic paper that provides Stefan–Boltzmann emissivity coefficients useful for infrared thermography applications involving snow.

Lundquist, J. D., C. Chickadel, N. Cristea, et al. “Separating Snow and Forest Temperatures with Thermal Infrared Remote Sensing.” *Remote Sensing of Environment* 209 (2018): 764–779.

This paper demonstrates how infrared imagery from a sensor mounted on an airplane relates to MODIS satellite observations and data collected on the ground at a field site in the Sierra Nevada (Yosemite National Park, California). The authors implement and test an algorithm that attempts to separate the temperatures in a “mixed pixel” infrared image comprised of forest and snowcover.

Pomeroy, J. W., D. S. Bewley, R. L. H. Essery, et al. “Shrub Tundra Snowmelt.” *Hydrological Processes* 20.4 (2006), 923–941.

The authors show how infrared thermal imagery of shrubs and snowcover at a subalpine tundra site (Wolf Creek, Yukon Territory, Canada) provides insight into spatial processes of radiative transfer. Between-pixel errors of the imager were identified as 0.2 °C, whereas the error across the entire image was 2 °C indicating that IR imagers are adequate for identifying spatial trends in snowpack processes in lieu of absolute accuracy.

Rees, W. G. "Infrared Emissivity of Arctic Winter Snow." ***International Journal of Remote Sensing*** **14.16 (1993): 3069–3073.**

Indicates that differences in emissivity can occur between winter and summer Arctic snowfall. The emissivity of Arctic snow ranged between 0.70 and 0.92 during the winter and was 0.99 during the summer. These emissivity numbers are important when temperatures of snow are calculated from IR imagery using the Stefan–Boltzmann law.

Schirmer, M., and B. Jamieson. "Limitations of Using a Thermal Imager for Snow Pit Temperatures." ***The Cryosphere*** **8.2 (2014): 387–394.**

The authors describe how an infrared camera can obtain thermal images indicative of spatial changes in temperature associated with the exposed wall of a snowpit. The experiments demonstrated complicating effects of wind, radiation, and air-snow temperature differences on the infrared measurements. The authors demonstrate that infrared camera measurements of snow pits cannot be used for accurate measurement of thermal gradients within the snowpack but are representative of heat transport processes.

Shea, C., and B. Jamieson. "Some Fundamentals of Handheld Snow Surface Thermography." ***The Cryosphere*** **5.1 (2011): 55–66.**

An excellent starting point for students or researchers who need to measure snowpack processes with thermal imagers, this paper establishes the basic theory and considerations related to calibration, subject distance, and atmospheric corrections. Effects of grain size on emissivity are discussed. The authors identify errors associated with transfer of heat to the snowpack by the operator holding the camera.

Shea, C., B. Jamieson, and K. W. Birkeland. "Use of a Thermal Imager for Snow Pit Temperatures." ***The Cryosphere*** **6.2 (2012): 287–299.**

The authors describe a procedure for measurement of thermal processes associated with snowpit wall temperatures that includes the effects of lens distortion and interpretation of temperature gradients. Phenomena associated with warming of a snow surface crust is identified. An image showing sub-surface heating of the snowpack is also presented.

Optical Properties

Perovich 2007 indicates how light reflection and transmission measurements can be made above and within the snowpack. Painter, et al. 2003 shows how a robotic arm with a spectroradiometer can obtain a hemispherical-directional reflectance factor (HDRF). Measurements to quantify the effects of dust on light reflection and transmission within the snowpack are described by Painter, et al. 2007 and Skiles and Painter 2017.

Painter, Thomas H., A. P. Barrett, C. C. Landry, et al. "Impact of Disturbed Desert Soils on Duration of Mountain Snow Cover. ***Geophysical Research Letters*** **34.12 (2007): L12502.**

The authors quantify the radiative effects of dust from desert soils on snowpacks in the San Juan Mountains. Models and data measurements showed the effects of a reduction in albedo on snowpack ablation.

Painter, T. H., B. Paden, and J. Dozier. “Automated Spectro-Goniometer: A Spherical Robot for the Field Measurement of the Directional Reflectance of Snow.” *Review of Scientific Instruments* 74.12 (2003): 5179–5188.

A spectroradiometer was placed on the end of a robotic arm and tilted at different angles to the snow surface at a field site location. The data was used to obtain a hemispherical-directional reflectance factor (HDRF) that characterized the anisotropic reflectance of light from the snow surface. Robot design, kinematics, calibration, and hardware is presented by the authors in this paper.

Perovich, D. K. “Light Reflection and Transmission by a Temperate Snow Cover.” *Journal of Glaciology* 53 (2007): 201–210.

Describes how detectors above and below the snow surface can be used to calculate albedo, extinction, and transmission coefficients. The author shows how new snowfall and ablation modifies the optical properties of the snowpack.

Skiles, S. M., and T. Painter. “Daily Evolution in Dust and Black Carbon Content, Snow Grain Size, and Snow Albedo during Snowmelt, Rocky Mountains, Colorado.” *Journal of Glaciology* 63.237 (2017): 118–132.

Snow pit measurement of snow particle size and spectrometer measurements were used along with laboratory optical analysis to quantify the effects of dust layers in snow.

Chemical Properties and Permeability

Chemical Sampling consists of techniques to quantify ions within the snowpack for characterization of chemical reactions or measurement of pollutants. Gas Flux measurements quantify gas transport between the soil, snowpack, and atmosphere. This also includes air transport for windpumping processes dependent on snowpack permeability. Darcy’s Law and the concept of permeability can be used to model transport of air, gas, and water through the snowpack. Specific Surface Area can be measured using gas adsorption techniques. See Snow Microstructure for optical techniques to measure Specific Surface Area (SSA).

Chemical Sampling

Grannas, et al. 2007 and Domine, et al. 2008 review photochemical processes occurring within the snowpack and discuss methods for chemical sampling and analysis. Douglas and Sturm 2004 and Nawrot, et al. 2016 demonstrate sampling of atmospheric pollutants from the snowpack. Pomeroy, et al. 1999 and Pelster, et al. 2009 present techniques of sampling and analysis used for characterization of chemical cycles in the boreal forest. Pomeroy, et al. 1991 indicates how blowing snow influences chemical processes and shows how data was collected and analyzed. Costa, et al. 2020 relates chemical samples collected at a field site in the Rocky Mountains to a mathematical model whereas Costa and Pomeroy 2019 shows how chemical samples were collected from melting snow placed inside of a box as a laboratory setup to study preferential flowpaths.

Costa, D., and J. W. Pomeroy. “Preferential Meltwater Flowpaths as a Driver of Preferential Elution of Chemicals from Melting Snowpacks.” *Science of The Total Environment* 662 (2019): 110–120.

A laboratory experiment was conducted that relates the spatial distribution of preferential flowpaths in a snowpack to ions transported by these flowpaths. Snow was placed inside of an insulated box with holes for capturing meltwater and a camera was utilized for tracking the flowpaths identified using dye tracer techniques.

Costa, D., G. A. Sexstone, J. W. Pomeroy, D. H. Campbell, D. W. Clow, and A. Mast. Preferential Elution of Ionic Solutes in Melting Snowpacks: Improving Process Understanding through Field Observations and Modeling in the Rocky Mountains. *Science of the Total Environment* 710 (2020): 136273.

This paper describes the chemistry and chemical dynamics of ions in snowmelt runoff collected by a lysimeter at a field site in the Rocky Mountains. Measurements by laboratory analysis and modeling demonstrated that processes associated with decreasing and variable concentrations of ions are dependent on an ion exclusion coefficient.

Domine, F., M. Albert, T. Huthwelker, et al. “Snow Physics as Relevant to Snow Photochemistry.” *Atmospheric Chemistry and Physics* 8.2 (2008): 171–208.

Provides an overview of the chemical processes occurring inside the snowpack as related to metamorphism, specific surface area (SSA), snow density, permeability, and thermal fluxes. Snowpack measurements are clearly related to the use of these measurements to drive models of chemical and physical processes.

Douglas, T. A., and M. Sturm. “Arctic Haze, Mercury and the Chemical Composition of Snow across Northwestern Alaska.” *Atmospheric Environment* 38.6 (2004): 805–820.

Describes a 1200 km transect with sixteen field sites where snowpits were used to extract samples for chemical analysis. The authors discuss the need for protective clothing worn by personnel to reduce contamination of snow samples. Sulfur, mercury, and trace elements in the snowpack were measured and related to atmospheric phenomena.

Grannas, A. M., A. E. Jones, J. Dibb, et al. “An Overview of Snow Photochemistry: Evidence, Mechanisms and Impacts.” *Atmospheric Chemistry and Physics* 7.16 (2007): 4329–4373.

A wide-ranging synthesis review of snow photochemistry indicating collection of data to characterize seasonal and diurnal variability of ions in the snowpack. Indicates the dynamics of processes related to nitrate and oxidant concentrations at sites ranging from the Arctic to the Antarctic.

Nawrot, A. P., K. Migała, B. Luks, P. Pakszys, and P. Głowacki. “Chemistry of Snow Cover and Acidic Snowfall during a Season with a High Level of Air Pollution on the Hans Glacier, Spitsbergen.” *Polar Science* 10.3 (2016): 249–261.

Describes the sampling and analysis of snow chemistry data on a glacier at a polar research station in Svalbard to characterize atmospheric pollution in the Arctic. The effects of mesoscale climate processes are discussed and quantified with respect to snow chemistry.

Pelster, D. E., R. K. Kolka, and E. E. Prepas. “Overstory Vegetation Influence Nitrogen and Dissolved Organic Carbon Flux from the Atmosphere to the Forest Floor: Boreal Plain, Canada.” *Forest Ecology and Management* 259.2 (2009): 210–219.

The chemical concentration of nitrogen ions in the snowpack was used along with measurements made during the snow-free season to characterize nitrogen and carbon cycles beneath the forest canopy in the boreal forest of western Canada. The paper provides a spatial sampling procedure.

Pomeroy, J. W., T. D. Davies, H. G. Jones, P. Marsh, N. E. Peters, and M. Tranter. “Transformations of Snow Chemistry in the Boreal Forest: Accumulation and Volatilization.” *Hydrological Processes* 13.14–15 (1999): 2257–2273.

This paper presents a study of boreal forest snow chemistry. The spatial distribution of nitrogen in snow is related to patterns of primary productivity, whereas sulphur is associated with atmospheric deposition of anthropogenic pollutants. Snow samples were collected from branches and snowpits; spatial changes in ion concentration was related to distance from tree trunks. The rate of intercepted snow sublimation affected nitrogen concentrations in the sub-canopy snowpack.

Pomeroy, J. W., T. D. Davies, and M. Tranter. “The Impact of Blowing Snow on Snow Chemistry.” Paper presented at the NATO Advanced Research Workshop on Processes of Chemical Change in Snowpacks held in Maratea, Italy, 23–27 July 1990. In *Seasonal Snowpacks*. Edited by T. D. Davies, M. Tranter, and H. G. Jones, 71–113. Berlin: Springer, 1991.

The authors provide a clear link between snow redistribution and snow chemistry. Surface snow erosion, blowing snow, and wind transport processes including saltation and suspension change the spatial distribution of ions in the snowpack. A link between sublimation and ion concentration enhancement is identified. During blowing snow events, atmospheric contaminants can be "scavenged" by snow particles transported by the wind. Measurements indicated changes in snowpack chemistry after blowing snow events.

Gas Flux

Hardy and Albert 1993 utilized a permeometer device to measure air permeability of snow by application of Darcy's Law. Albert and Hardy 1995 describes an experiment with a fan used to quantify the movement of air through the snowpack using a permeometer and mathematical modeling. Flux chambers to quantify the flow of gas were utilized by McDowell, et al. 2000; Welker, et al. 2000; and Medinets, et al. 2016. Gas analyzers with tubing deployed in the snowpack are described by Seok, et al. 2009 and Zhu, et al. 2014.

Albert, M. R., and J. P. Hardy. "Ventilation Experiments in a Seasonal Snow Cover." In *Biogeochemistry of Seasonally Snow-Covered Catchments*. IAHS Publication no. 228. Edited by K. Tonnessen, M. W. Williams, and M. Tranter, 41–49. Wallingford, UK: IAHS Press, 1995.

The authors used a fan to force air through the snowpack to induce a change in pressure. Resulting changes in temperature were quantified by a thermocouple array buried in the snowpack. Modeling supported the conclusion that small variations in pressure resulted in large volumes of air movement through snow responsible for changing the temperature of the snowpack.

Hardy, J. P., and D. G. Albert. "The Permeability of Temperate Snow: Preliminary Links to Microstructure." *Proceedings of the Eastern Snow Conference* 50 (1993): 149–156.

The authors provide a schematic diagram of a permeometer and associated theory related to Darcy's Law that allows snow permeability to be measured. Snow permeability is important to measure since it influences heat transport through snow, affects snowpack metamorphism and governs the timing of meltwater propagation.

McDowell, N. G., J. D. Marshall, T. D. Hooker, and R. Musselman. "Estimating CO2 Flux from Snowpacks at Three Sites in the Rocky Mountains." *Tree Physiology* 20.11 (2000): 745–753.

Describes the use of flux chambers to characterize the transport of carbon dioxide from snow to the atmosphere. A chamber was deployed on the snow surface and attached to a portable infrared gas analyzer. Gas samples were taken from soil using a flux chamber deployed at the bottom of a snowpit. Temporal and spatial relationships affecting carbon dioxide flux between sites was identified.

Medinets, S., R. Gasche, U. Skiba, A. Schindlbacher, R. Kiese, and K. Butterbach-Bahl. "Cold Season Soil NO Fluxes from a Temperate Forest: Drivers and Contribution to Annual Budgets." *Environmental Research Letters* 11.11 (2016): 114012.

To quantify nitric oxide gas fluxes from acidic forest soils, flux chambers were placed on the forest floor of the Höglwald Forest, Germany, during the summer and winter. During sampling, the flux chambers were connected to gas chromatographs. Winter measurements were influenced by the presence of a snow layer with an average depth of 4.6 cm.

Seok, B., D. Helmig, M. W. Williams, D. Liptzin, K. Chowanski, and J. Hueber. "An Automated System for Continuous Measurements of Trace Gas Fluxes through Snow: An Evaluation of the Gas Diffusion Method at a Subalpine Forest Site, Niwot Ridge, Colorado." *Biogeochemistry* 95.1 (2009): 95–113.

Describes an elaborate measurement apparatus comprised of a tower with measurement tubes situated at vertical sampling heights above the ground surface. The tubes were connected to solenoid valves and an infrared gas analyzer situated in an underground room near the tower. Snow accumulated around the tower and the tubes. An automated system controlled the solenoid valves and the gas analyzer to measure trace gases in the snowpack.

Welker, J. M., J. T. Fahnestock, and M. H. Jones. "Annual CO2 Flux in Dry and Moist Arctic Tundra: Field Responses to Increases in Summer Temperatures and Winter Snow Depth." ***Climatic Change*** **44.1 (2000): 139–150.**

Demonstrates how carbon dioxide flux measurements at an Arctic tundra site can be related to snowcover. The experimenters conducted flux chamber measurements on two different types of tundra land surfaces and increased snow depth by erecting snow fences to trap snow.

Zhu, C., M. Nakayama, and H. Yoshikawa Inoue. "Continuous Measurement of CO2 Flux through the Snowpack in a Dwarf Bamboo Ecosystem on Rishiri Island, Hokkaido, Japan." ***Polar Science*** **8.3 (2014): 218–231.**

A similar setup to the Seok, et al. 2009 paper with a vertical tower frame deployed on Rishiri Island, Japan. The frame was smaller than the one used in the Seok, et al. 2009 paper due to a lesser height of snow. Diurnal variability of fluxes was quantified for this environment.

Specific Surface Area

Legagneux, et al. 2002 describes the technique of using gas absorption to measure Specific Surface Area (SSA). Dominé, et al. 2001 compares the gas absorption technique to other methods, finding that gas absorption is more accurate than microscopy for measurement of SSA.

Dominé, F., A. Cabanes, A.-S. Taillandier, and L. Legagneux. "Specific Surface Area of Snow Samples Determined by CH4 Adsorption at 77 K and Estimated by Optical Microscopy and Scanning Electron Microscopy." ***Environmental Science & Technology*** **35.4 (2001): 771–780.**

Methane absorption for determination of SSA was compared to optical and electron microscope methods. The authors indicate that the gas adsorption method provides estimates that are more suitable for mathematical modeling calculations involving gas fluxes. Optical microscopy methods were found to be less accurate than the gas adsorption method.

Legagneux, L., A. Cabanes, and F. Dominé. "Measurement of the Specific Surface Area of 176 Snow Samples Using Methane Adsorption at 77 K." ***Journal of Geophysical Research: Atmospheres*** **107.D17 (2002): ACH 5-1–ACH 5-15.**

The authors provide an apparatus and related theory indicating how methane absorption by a snow sample is related to the specific surface area (SSA). Sources of error and sensitivity of the method is described. An experimental laboratory setup with a pump, compressed gas, and a liquid nitrogen cooling chamber is required.

Mechanical Properties

Shear frames and associated devices to measure snow mechanical properties are described by Keeler and Weeks 1968; Perla 1969; Perla, et al. 1982; Perla and Beck 1983; and Föhn, et al. 1998. Measurement devices specifically designed for assessing skiing conditions are described by Mössner, et al. 2013. The "SnowMicroPen" penetrometer to measure snowpack layering and hardness is described by Schneebeli and Johnson 1998; Johnson and Schneebeli 1999; and Schneebeli, et al. 1999.

Föhn, P. M. B., C. Camponovo, and G. Krüsi. "Mechanical and Structural Properties of Weak Snow Layers Measured in Situ." ***Annals of Glaciology*** **26 (1998): 1–6.**

This paper describes how shear frames are used to estimate the mechanical properties of weak layers in the snowpack that are prone to structural failure. The authors examine relationships between snow particle structure and the shear strength of a layer.

Johnson, J. B., and M. Schneebeli. “Characterizing the Microstructural and Micromechanical Properties of Snow.” *Cold Regions Science and Technology* 30.1–3 (1999): 91–100.

The authors present a model that relates snow mechanical properties to snow structure. The model was used to characterize the physics of SnowMicroPen operation.

Keeler, C. M., and W. F. Weeks. “Investigations into the Mechanical Properties of Alpine Snow-Packs.” *Journal of Glaciology* 7.50 (1968): 253–271.

The authors provide an overview of devices used to measure the mechanical properties of snow. These devices include the Rammsonde as a cone penetrometer to obtain a coefficient that indicates the compressive strength and hardness of a snowpack. A centrifuge was used to determine tensile strength and shear frames measured shear strength. The use of shear vane devices is also discussed by the authors.

Mössner, M., G. Innerhofer, K. Schindelwig, P. Kaps, H. Schretter, and W. Nachbauer. “Measurement of Mechanical Properties of Snow for Simulation of Skiing.” *Journal of Glaciology* 59.218 (2013): 1170–1178.

The authors provide a useful overview of snowpack measurements for characterizing skiing conditions. This paper describes a novel snow penetration force measurement device and a shear force device to quantify snow hardness and failure shear stress. A simple model of forces associated with skiing is also presented.

Perla, R. “Strength Tests on Newly Fallen Snow.” *Journal of Glaciology* 8 (1969): 427–440.

This paper shows how mechanical strength tests can be applied to snow of low and high density. The author clearly describes penetrometer, shear frame, shear vane, and cantilever beam measurements.

Perla, R., and T. M. H. Beck. “Experience with Shear Frames.” *Journal of Glaciology* 29 (1983): 485–491.

This paper describes the theory, design, and deployment of shear frames to measure snow. Alignment of the shear frame during sampling is discussed for accurate measurements.

Perla, R., T. M. H. Beck, and T. T. Cheng. “The Shear Strength Index of Alpine Snow.” *Cold Regions Science and Technology* 6 (1982): 11–20.

The authors present techniques for snow shear strength measurements using shear frames and rotary vanes. Shear strength is related to density by an empirical relationship.

Schneebeli, M., and J. B. Johnson. “A Constant-Speed Penetrometer for High-Resolution Snow Stratigraphy.” *Annals of Glaciology* 26 (1998): 107–111.

This paper describes an early prototype of the SnowMicroPen, a device with a force transducer that is used to measure snowpack layering.

Schneebeli, M., C. Pielmeier, and J. B. Johnson. “Measuring Snow Microstructure and Hardness Using a High Resolution Penetrometer.” *Cold Regions Science and Technology* 30.1 (1999): 101–114.

This paper showed how the SnowMicroPen is used to obtain measurements of a snow texture index. Penetration resistance force is related to snow microstructure and the detection of weak layers in the snowpack.

back to top