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Data for snowmelt model development, calibration, and verification at an alpine site, Colorado Front Range

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Abstract. Logistical constraints have caused data collection in seasonally snow covered areas to generally be on a campaign basis with limited instrumentation. The problems of winter access, cold air temperatures, and blowing snow cause both equipment malfunctions and problems with consistent and timely maintenance. At the Long-Term Ecological Research program network site in an alpine area of Colorado we have been operating a meteorological station and subnivean (below snow) laboratory at 3517 m since the spring of 1994 to collect information that will allow us to better understand snow-surface energy exchanges and the mass flux of water during snowmelt. This unique and high-quality data set was designed to measure the meteorologic and hydrologic parameters necessary to compute the surface energy and snowpack mass balances at a point. All meteorological parameters are directly measured. Turbulent fluxes are calculated using the aerodynamic profile method. The timing and magnitude of snowmelt is measured with 18 snow lysimeters. Meteorologic parameters and energy fluxes are available at 10-min, hourly, and daily time steps. Complementary information includes a high-resolution digital elevation model, snowpack parameters, and stream discharge.

1. Introduction

In most northern and alpine environments, snowmelt runoff is responsible for both the annual maximum instantaneous discharge and a major portion of the annual flow [*Marsh and Woo*, 1985]. Understanding and predicting the response of hydrologic and biogeochemical transfers within snowmelt-dominated basins to climate variability and change requires a thorough understanding of the energy transfers between the snowpack and the atmosphere that lead to changes in the internal energy of the snowpack and eventually cause snowmelt [*Cline*, 1997a]. One of the greatest challenges facing snow scientists today is the internal dynamics of the snowpack as meltwater infiltrates from the snow surface into the snowpack [*Colbeck*, 1991]. Additionally, point energy balance experiments provide an opportunity to test physically based point snowmelt models (such as SNTHERM [*Jordan*, 1991]) under conditions characteristic of a specific location. Processed-based snowmelt models such as SNTHERM are increasingly used in a spatial context to meet the needs of a variety of hydrological, hydrochemical, and geomorphological applications in alpine regions [*Kirnbauer et al.*, 1994; *Harrington et al.*, 1995]. To build confidence in our understanding of snow-atmosphere energy transfers, to better understand meltwater flow through snow, and to build confidence in our ability to spatially distribute point snowmelt models, it is important to carefully evaluate model performance under field conditions.

Logistical constraints have caused data collection in seasonally snow-covered areas for parameterizing and verifying energy-balance snowmelt models to be on a campaign basis with limited instrumentation. The problems of winter access, cold air temperatures, and blowing snow cause both equipment malfunctions and problems with consistent and timely maintenance. At the Long-Term Ecological Research (LTER) program network site in an alpine area of Colorado we have been operating a meteorological station and subnivean (below snow) laboratory at 3517 m since the spring of 1994 to collect information that will allow us to better understand snow-surface energy exchanges and the mass flux of water during snowmelt. This unique and high-quality data set was designed to measure the meteorologic and hydrologic parameters necessary to compute the surface energy and snowpack mass balance at a point through time. Consequently, this data set provides the basis for snowmelt model development, calibration, and verification.

Ancillary data such as snow stratigraphy and grain size provide additional information to improve our process-based understanding of snow phenomenon at a point. The meteorological instrumentation operates continuously and also provides data on energy fluxes over alpine tundra during the snow-free season. Spatial data are also available that provide the basis for developing and testing snowmelt models at the catchment scale. A high-resolution (10 m) digital elevation model (DEM) combined with continuous discharge information provide the basis for testing snowmelt models in a spatially distributed mode [e.g., *Harrington et al.*, 1995; *Cline et al.*, 1998].

Data acquisition, trouble shooting, storage, and access are supported as part of the Niwot Ridge LTER program funded by the National Science Foundation. In the expectation that these data will be useful to other researchers, we are making the data available following the guidelines of *Hornberger* [1994].

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2. Data Acquisition

2.1. Site Description

The instrument site is located at 3517 m elevation on Niwot Ridge on the eastern slope of the Front Range of Colorado (40°03'N, 105°35'W). Niwot Ridge is a 10-km interfluve extending eastward from the Continental Divide and is characterized by low rounded hills with shallow saddles (Figure 1). Tree line in this area is at approximately 3350 m. The instrument site is located on a flat bench above tree line within a broad saddle of the ridge (Figure 1). The high elevation, exposure, and typically dry atmospheric conditions of Niwot Ridge result in long periods with clear-sky atmospheric transmissivity, high solar insolation, low magnitudes of incident longwave radiation, low air temperatures, and high wind velocities. From 1951 to 1993, mean annual temperature on Niwot Ridge was −3.8°C, and annual precipitation was 1000 mm [*Williams et al.*, 1996], with about 80% falling as snow [*Caine*, 1996]. Niwot Ridge forms the northern boundary of Green Lakes Valley (Figure 1) and is an UNESCO Biosphere Reserve and an LTER network site. The Green Lakes Valley is an east facing headwater catchment that is 700 ha in area and ranges in elevation from 3250 m to just over 4000 m.

2.2. Data Measurements

Meteorological measurements are made on a 7-m mast located approximately 20 m from the subnivean laboratory. Upward and downward looking shortwave radiation is measured with a Kipp and Zonen CM 14 pyranometer; upward and downward looking longwave radiation is measured with a Kipp and Zonen CG 2 pyrgeometer (Table 1). Net radiation is measured with a REBS Q*7, which provides both a quality control check on the pyranometer and pyrgeometer as well as redundancy in the event of a malfunction in one of the radiometers. Paired LiCor LI-200 SA pyranometers provide measurements of direct and diffuse solar radiation, with one unshaded and the second having a shadow band.

Turbulent fluxes are computed using the aerodynamic profile method, with one instrument array at a fixed height of 6 m above the ground and three instrument arrays that are mounted on a mast that is moved by hand to maintain fixed instrument heights above the snow surface of 0.5, 1.0, and 2.0 m. Air temperature and relative humidity are measured at each height with a Vaisala HMP35c probe housed in a Gill 12-plate radiation shield (Table 1). The shield is not ventilated because of the consistent and high wind velocities characteristic of Niwot Ridge. These instruments are calibrated by placing them on the same level and calibrating to a single instrument, since our primary concern is the relative accuracy among levels for calculation of sensible and latent heat fluxes using the aerodynamic profile method. Wind speed and direction are measured using RM Young 05103 wind monitors which have a range of 0–60 m s^{-1} and a gust survival velocity of 100 m s^{-1}; calibration is conducted with an RM Young electric motor.

Snow depth is measured with a Campbell Scientific Instruments UDGO1-1 sonic anemometer (Table 1). Soil heat flux is measured directly using a REBS HFT-1 soil heat flux plate installed at a depth of 5 cm. Barometric pressure is measured by capacitance with an AIR-DB-2BX. The timing, magnitude, and spatial variability of snowmelt is measured using a system of snow lysimeters (two 1-m^2 lysimeters and sixteen 0.2-m^2 lysimeters deployed in a circle with a 10-m diameter) that drain by gravity into dedicated tipping buckets housed in the subnivean laboratory. The two 1-m^2 lysimeters drain into Campbell Scientific TE525 tipping bucket rain gages, and the sixteen 0.2-m^2 lysimeters drain into Davis Instruments rain collector II tipping bucket gages.

Meteorological variables are measured every 10 s; means and standard deviations of the data are computed and stored at 10-min intervals. Data, such as tipping bucket counts, are totalized and stored at 10-min intervals. Data are recorded on Campbell Scientific CR21x and CR10 data loggers and stored on a Campbell CSM1 storage module which is changed each Tuesday.

Instrument records for most instruments began in April 1994 and continue to the present (Table 1). Instrument problems do occasionally occur. A complementary meteorological station (tundra laboratory) is located 150 m east of the subnivean site and includes measurements of solar radiation, air temperature, relative humidity, barometric pressure, wind speed, and wind direction at one height, with all measurements beginning before April 1994 (Figure 1). These measurements can be used to fill missing data gaps at the subnivean site.

Snow properties are analyzed weekly (usually beginning in January when snow depths exceed 0.50 m) at pit 006 located 50 m to the north of the meteorological tower, following the protocol of *Elder et al.* [1991] and *Williams and Melack* [1991] (Figure 1). Snow density is measured in vertical increments of 10 cm using a 1-L (1000 cm^3) stainless steel cutter and an electronic scale (±2 g). Temperature of the snowpack is measured every 10 cm with 20-cm-long dial stem thermometers, calibrated to ± 0.2°C using a one-point calibration at 0°C. Grain type, size, and snowpack stratigraphy are also recorded. Depth-weighted values are then calculated for snowpack density, temperature, and water equivalent. The snowpack is sampled for major solute chemistry in increments of 40 cm beginning just prior to the initiation of snowmelt and weekly through the melt season. Meltwater from the two 1-m^2 snow lysimeters is collected as grab samples on an opportunistic basis and analyzed for major solutes. Additionally, 6 to 12 snow pits spatially distributed over Niwot Ridge and Green Lakes Valley are sampled at maximum snow accumulation for the above physical and chemical properties.

Field personnel service the site on a daily basis each weekday, examining the instruments, checking the data-recording equipment, raising or lowering the aerodynamic profile instrument array, and making weather observations. These metadata are added through an electronic menu system and come bundled with the data set. Data are retrieved from the field site on a weekly basis (Tuesdays) and downloaded onto a workstation.

Complementary data sets that may be of interest include meteorological information from three additional sites on and near Niwot Ridge (D1, Green Lake 4, and Arikaree, see Figure 1) and daily discharge from the nearby Martinelli and Green Lake 4 catchments (Figure 1). Distributed maps of snow water equivalence at maximum accumulation for Green Lakes Valley are available starting in 1997.

2.3. Data Protocol

2.3.1. Meteorological data. There are four levels of data.

1. Level 0 data are the raw data that is downloaded from the data loggers. It is permanently achieved in the original format and as such is mostly uncalibrated, not converted to meaningful units, and unfiltered. Interpretation of these data requires ancillary information, such as calibration coefficients.
2. Level 1 data are calibrated, filtered (outliers removed),

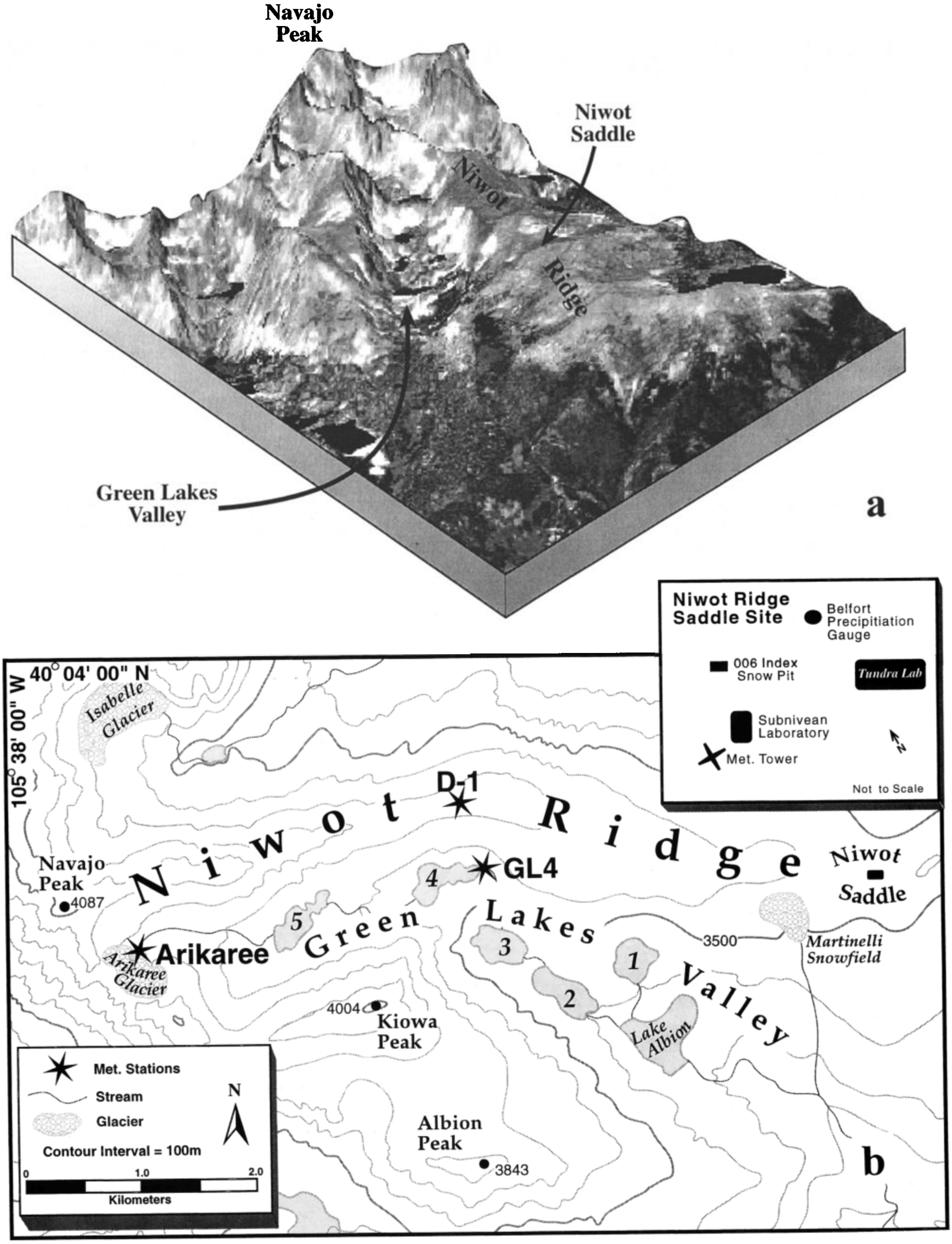

Figure 1. (a) Niwot Ridge, Green Lakes Valley, and surrounding areas represented by a digital 1:40,000 orthophoto draped over a high-resolution digital elevation map made by Analytical Surveys, Inc., Colorado Springs. (b) Topographic map of Niwot Ridge and Green Lakes Valley showing the location of the subnivean laboratory on Niwot Ridge, ancillary meteorological stations (marked with stars), with gaging stations located at the outlets of the Martinelli and Green Lake 4 catchments.

Table 1. Meteorological Parameters, Instrumentation, and Record Length

Parameter	Instrument	Model	Range	Accuracy	Record Length
$K\downarrow$, $K\uparrow$	pyranometer	Kipp and Zonen CM 14	305 to 2800 nm	±5%	April 1994 to present
$L\downarrow$, $L\uparrow$	pyrgeometer	Kipp and Zonen CG 2	5 to 25 μm	±10%	April 1994 to present
Q^*	net radiometer	REBS Q*7	0.25 to 60 μm	±5%	April 1994 to present
T	thermistor	Vaisala HMP35c	−33°C to +48°C	±0.4°C	April 1994 to present
RH	capacitance	Vaisala HMP35c	0 to 100%	±1%	April 1994 to present
u	propeller	Young 05103	0 to 60 m s^{-1}	±2%	April 1994 to present
P	capacitance	AIR-DB-2BX	600 to 1060 mbars	±0.5 mbars	June 1994 to present
G	transducer	REBS HFT-1	0 to ±500 W m^{-2}	±5%	May 1994 to present
z	transducer	UDGO1-1	0.10 to 6 m	±1 cm	April 1994 to present

Abbreviations are as follows: K is shortwave radiation; L is long-wave radiation; Q^* is net radiation; T is air temperature; RH is relative humidity; u is wind speed; P is barometric pressure; G is soil heat flux, and z is snow depth.

10-min meteorological data and energy flux calculations. Notes, observations, and problems are recorded in the metadata system, which is bundled with the data request.

3. Level 2 data are the 10-min data averaged over hourly and daily time intervals. All fluxes are available. Relative humidity, air temperature, and wind speed are only available at the 2-m height.

4. Level 3 data are segments of the database that have undergone rigorous analysis by one or more of the project scientists and have been published [e.g., *Cline*, 1997a, b].

2.3.2. Spatial data. The Niwot Ridge LTER has acquired a high-resolution DEM at the regional level, developed by Analytical Surveys, Incorporated in Colorado Springs. The DEM and corresponding digital orthophotos are for a 10.5-km (E/W) by 5.4-km (N/S) area that encompasses the Mountain Research Station, Niwot Ridge, Green Lakes Valley, and the Continental Divide (Figure 1). The DEM was developed from 1:12,000-scale black and white aerial photography to collect break lines and mass points in the Green Lakes Valley area for capture of any feature larger than 10 m. Then 1:24,000-scale color infrared (CIR) aerial photographs were utilized for feature capture on Niwot Ridge, and 1:40,000-scale CIR aerial photographs were used to fill in the study area margins. Break lines and mass points were collected at a coarser resolution as photograph scale decreased. Digital orthophotos were generated from all three scales of photography.

A number of spatial products based on the DEM CIR aerial photographs are also available. Slope, aspect, and shaded relief maps were generated from the DEM using algorithms in Erdas Imagine software. The slope and aspect data are given in degrees (an aspect of 361 is flat). The shaded relief image was produced using an illumination azimuth angle of 315° and vertical angle of 60° above the horizon, with 5% ambient illumination. Maps of the area are available for hydrography, soils, geology, and landscape types. Spatial maps of snow depth at maximum accumulation were developed using a combination of several hundred field measurements of snow depth and kreiging; original snow depth information along with universal transverse mercator coordinates are available. Metadata are available for these maps.

3. Data Access, Format, and Precision

Data are accessed from the internet, in ascii files that are space delimited (http://www.nsidc.colorado.edu/NOAA/wdc-a.html). The data can be parsed in a variety of ways using a series of on-line forms. The data are subdivided into meteorological and flux data for the time period selected by the user. Meteorological data are further subdivided into instrument type and height of instrument. Level 3 data come as a bundled set, such as the data used by *Cline* [1997a, b]. Information on instrument type, manufacture, and precision is provided at the data site. See *Cline* [1997a, b] for an overview. The color infrared orthophotos, DEM, and spatial maps may be downloaded in one or more of the following formats: Erdas Imagine format, generic binary format, and tiff image. Additional information is available at the Niwot Ridge LTER web site (http://culter.colorado.edu:1030/).

4. Examples of Use of Data

Process-driven snowmelt models incorporate our best knowledge of the physical processes that determine energy transfers at the snow-atmosphere interface. Comparison of modeled versus measured snowmelt permits model testing and verification. A comparison of modeled versus measured snowmelt for the 1994 snowmelt season shows that cumulative snowmelt measured in snow lysimeters was comparable to the three model outputs (Figure 2). An outstanding problem in snow hydrology is the fate of meltwater produced at the snow surface after infiltration into the snowpack. For example, the irreducible water saturation (analogous to the field capacity of

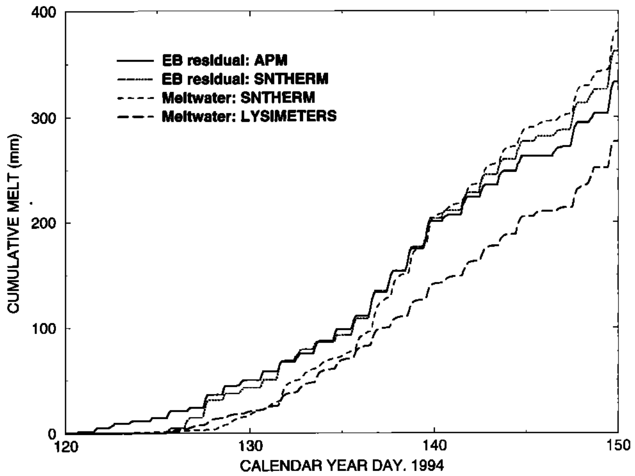

Figure 2. A comparison of cumulative snowmelt amounts using (1) the energy balance residual using the aerodynamic profile method to measure turbulent fluxes, (2) the energy balance residual using SNTHERM to calculate energy fluxes, (3) SNTHERM to calculate snowmelt, and (4) snowmelt measured in a 1-m^2 snow lysimeter.

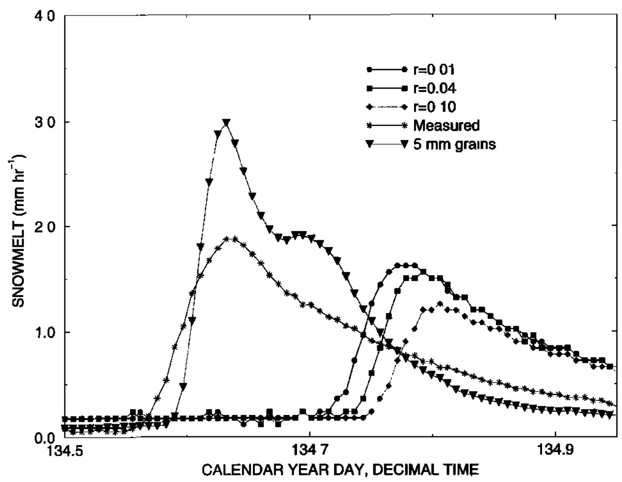

Figure 3. A time series of measured and modeled snowmelt at Niwot Ridge 1994. The irreducible water saturation for snow (r) in the energy-balance model SNTHERM varies over an order of magnitude. Increasing grain size in the model reduced the time lag between measured and modeled snow melt.

soils) has a large effect on the lag time between meltwater generation at the top of the snowpack and the release of meltwater at the bottom of the snowpack. However, the irreducible water saturation for snow is not known. Using SNTHERM, we compare how changes in the irreducible water saturation change the timing and magnitude of meltwater flux and compare the results to measured snowmelt (Figure 3).

5. Summary

High-quality and temporally extensive data sets to calibrate and validate energy-balance snowmelt models are sparse. Meteorological, snowpack, and snowmelt data collected since 1994 are described and are available for analysis. These data are also appropriate for additional analyses, including energy fluxes over alpine tundra and calculation of sublimation/condensation rates to and from the snow surface. The data can be parsed in a variety of ways using on-line forms. From users of these data we ask for copies of Level 3 data that we can post. We are interested in feedback on ways to improve data availability and quality.

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