



NASA Cold Land Processes Experiment (CLPX 2002/03): Ground-Based and Near-Surface Meteorological Observations

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ABSTRACT

A short-term meteorological database has been developed for the Cold Land Processes Experiment (CLPX). This database includes meteorological observations from stations designed and deployed exclusively for CLPX as well as observations available from other sources located in the small regional study area (SRSA) in north-central Colorado. The measured weather parameters include air temperature, relative humidity, wind speed and direction, barometric pressure, short- and longwave radiation, leaf wetness, snow depth, snow water content, snow and surface temperatures, volumetric soil moisture content, soil temperature, precipitation, water vapor flux, carbon dioxide flux, and soil heat flux. The CLPX weather stations include 10 main meteorological towers, 1 tower within each of the nine intensive study areas (ISA) and one near the local scale observation site (LSOS); and 36 simplified towers, with one tower at each of the four corners of each of the nine ISAs, which measured a reduced set of parameters. An eddy covariance system within the North Park mesocell study area (MSA) collected a variety of additional parameters beyond the 10 standard CLPX tower components. Additional meteorological observations come from a variety of existing networks maintained by the U.S. Forest Service, U.S. Geological Survey, Natural Resource Conservation Service, and the Institute of Arctic and Alpine Research. Temporal coverage varies from station to station, but it is most concentrated during the 2002/03 winter season. These data are useful in local meteorological energy balance research and for model development and testing. These data can be accessed through the National Snow and Ice Data Center Web site.

1. Introduction

Meteorological measurements are sparse in most seasonally snow-covered mountain areas, and data typically includes only the most basic parameters. Spatially distributed meteorological datasets suitable for hydrological modeling are rare and tend to concentrate on small regions or specific environments (e.g., Williams et al. 1999; Hanson 2001; Hanson et al. 2001). Regional datasets with local detail are even less common. Local and regional energy balance controls hydrological response at the plot, hillslope, and watershed scale.

The NASA Cold Land Processes Experiment (CLPX) was designed to facilitate significant advances in snow and cold regions hydrology (Cline et al. 2002). There were two major components to the field experiment: airborne remotely sensed data acquisition (Cline et al. 2009) and an extensive ground-based survey effort. A network of ground-based meteorological observation stations was deployed within the CLPX study area (D. Cline 2008, unpublished manuscript). The purpose of measuring the meteorological parameters was to quantify variability from local to regional scales within various snow environments and to archive forcing data for algorithm and model development and verification. The network included 10 main meteorological towers and one eddy covariance site. Data from these sites and other existing meteorological networks provided a high-quality dataset with nested spatial coverage.

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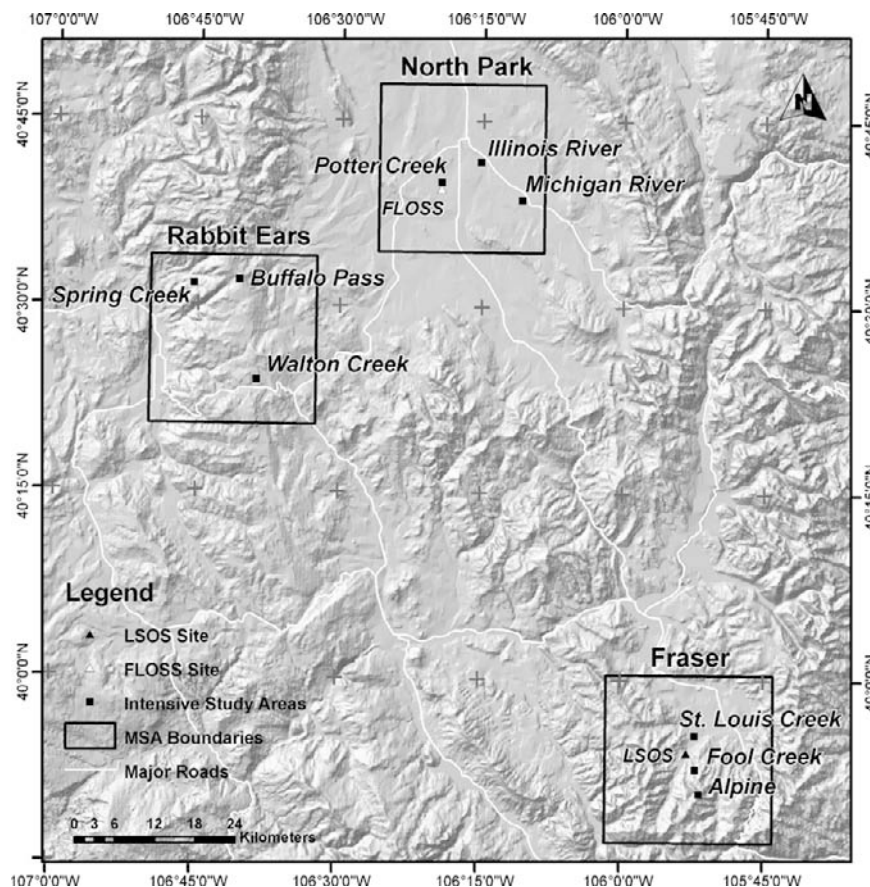


FIG. 1. Map of field locations. The main meteorological sites were located near the middle of the 1-km² field sites; the 36 corner site stations were located at the corners of each of the nine ISAs. Although the figure does not provide local site topography, it does give relative location and gross area topography.

Additional spatial datasets were collected during the study period using existing satellite platforms, and imagery may be found in the data archive.

2. CLPX ground-based meteorological observation network

a. Main meteorological towers

Ten identical 12-m instrument towers were erected at CLPX study sites during the summer of 2002: nine towers were located near the center of the nine intensive study area (ISA) locations, and one tower was located adjacent to the local scale observation site (LSOS; Fig. 1). Upper-level measurements were taken 10 m above the ground surface. Lower-level measurements were collected 2–4 m above ground level, depending on anticipated maximum snow depth. Lower measurements were made at 2 m above ground level in the North Park mesocell study area (MSA; shallow and

transient snowpacks), 3 m above ground level in the Fraser MSA (moderate snowpacks), and 4 m above ground level in the Rabbit Ears MSA (deep snowpacks). Air temperature, relative humidity, wind speed, and wind direction were measured at 10 m and at the lower crossarm height. Radiation and leaf wetness were measured at 10 m. Radiation was measured by two net radiometers, one of which partitioned the radiation into component values (incoming and outgoing short- and longwave). Barometric pressure, snow depth, and surface temperature were measured at the level of the lower cross arm. Volumetric soil moisture content and soil temperature were measured at 0.05, 0.20, and 0.50-m depth below ground level. Snowpack temperature profiles were measured on a suspended thermocouple string at 20 levels from the ground surface to the height of the lower cross arm at 0.10, 0.15, and 0.20 m increments in the North Park, Fraser, and Rabbit Ears MSAs, respectively. Soil temperatures were measured

TABLE 1. Parameters, specifications, and instruments used on meteorological towers.

Observation	Height above ground (m)	Sampling interval	10-min summaries	Accuracy (manufacturer specified)	Model
Wind speed	10 2–4	30 s	average maximum minimum	$\pm 2\%$	R.M. Young Wind Monitor 05103
Wind direction	10 2–4	30 s	average sample std dev	$\pm 5^\circ$	R.M. Young Wind Monitor 05103
Air temperature	10 2–4	30 s	average	$\pm 0.5^\circ\text{C}$	Vaisala HMP45C
Air relative humidity	10 2–4	30 s	average maximum minimum	$\pm 3\%$	Vaisala HMP45C
Snow depth	2–4	30 s	sample	± 0.01 m	Judd Communications depth sensor
Component and net radiation	10	30 s	average (for each component)	$\pm 10\%$ (daily totals)	Kipp and Zonen CNR 1 net radiometer
Net radiation	10	30 s	average	$\pm 20\%$	Kipp and Zonen NR Lite net radiometer
Soil moisture	–0.05 –0.20 –0.50	10 min	sample	± 0.03 water fraction by volume	Stevens Vitel Hydra Probe
Soil temperature	–0.05 –0.20 –0.50	10 min	sample	$\pm 0.6^\circ\text{C}$	Stevens Vitel Hydra Probe
Soil temperature	–0.05 –0.20 –0.50	30 s	average	$\pm 1^\circ\text{C}$	Type T copper-constantan thermocouple wire
Leaf wetness	10	30 s	average	NA	Campbell Scientific Model 237 leaf wetness sensor
Surface temperature	2–4	30 s	average	$\pm 0.4^\circ\text{C}$	Apogee IRTS-P5 infrared thermocouple
Atmospheric pressure	2–4	30 s	average	± 6 mb	Vaisala PTB101B pressure transmitter
Precipitation	2	30 s	average	± 1.0 mm	Belfort weighing rain gauge retrofitted with Rice Lake Weighing Systems load cell

on the same thermocouple string at 0.00, 0.05, 0.20, and 0.50 m. Precipitation was measured within the North Park MSA in Belfort gauges with Alter shields. All precipitation gauges were retrofitted with electronic load cells. Details of the instruments and measured parameters are listed in Table 1.

Data collection began in late September 2002 for the ISA towers and mid-November 2002 for the LSOS site. Measurements were made every 30 s and averaged over 10-min intervals for all parameters, except for soil moisture and snow depth measurements, which were recorded instantaneously at 10-min intervals. Continuous data were logged through the end of the 2003 water year, except for the Illinois River and Potter Creek towers, which were removed in July 2003 because of land use agreements. Figure 2 shows a schematic of

relative locations of instruments on the towers. Figure 3 shows the Michigan River meteorological tower and precipitation gauge.

b. Corner site meteorological towers

A secondary network of meteorological towers was deployed at each of the four corners of each of the nine ISAs, giving a total of 36 sites where a reduced set of parameters were measured. Each tower consisted of a guyed 4-m aluminum pole with a cross arm for instruments. Instruments were mounted on the cross arm 2 m above ground level in the North Park MSA and 4 m above the ground in the Fraser and Rabbit Ears MSAs. The parameters measured included air temperature, relative humidity, wind speed and direction, snow

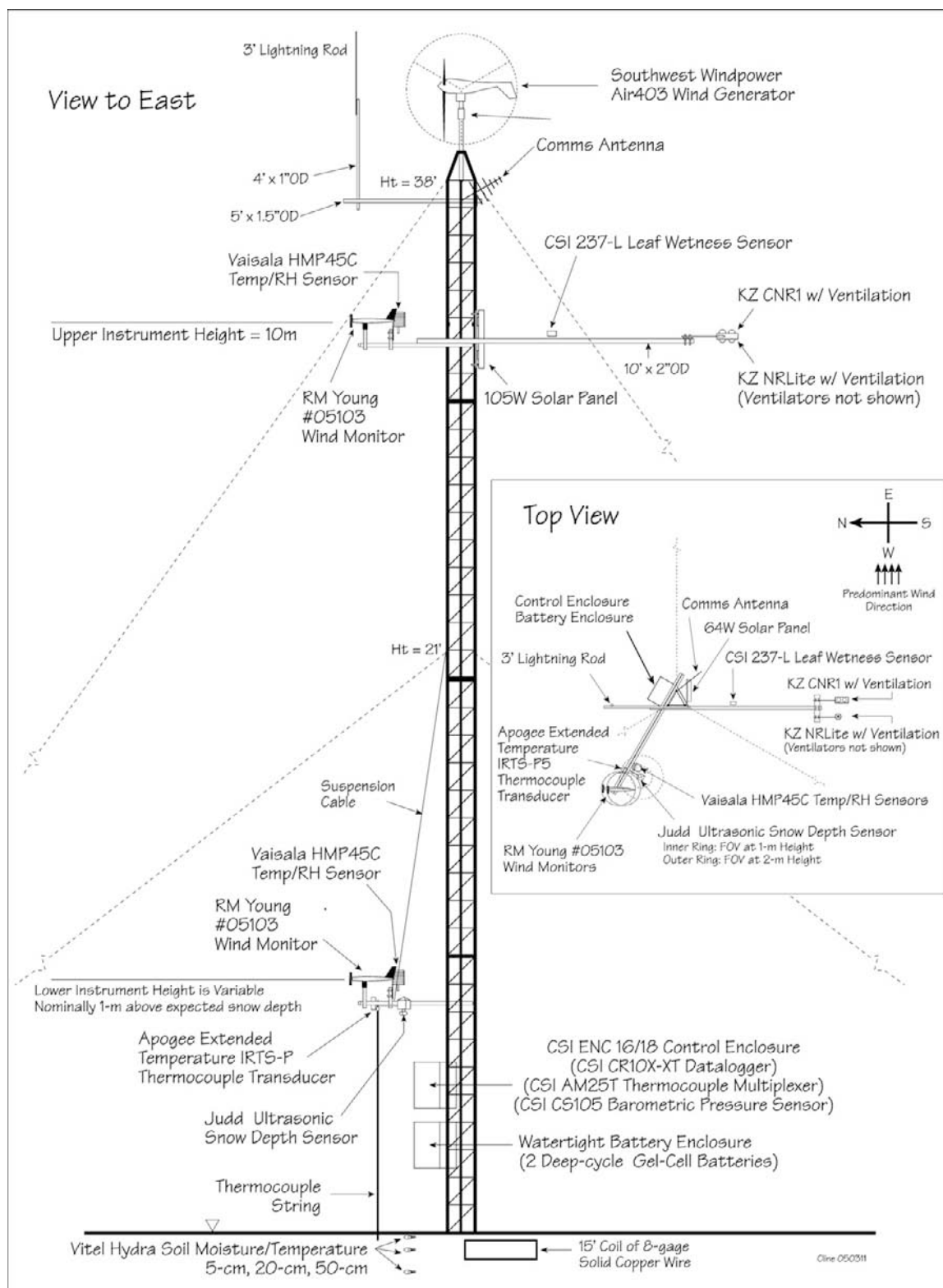


FIG. 2. Schematic of main meteorological towers and instrument locations.



FIG. 3. Michigan River meteorological tower and shielded precipitation gauge located at 2600 m MSL. in the North Park MSA, near Walden, Colorado. Stakes shown in the photograph held wire for an electric fence to protect the site from livestock and elk herds frequenting the area.

depth, soil moisture, and soil temperature. Data collection at these 36 corner sites was designed with a different intent and practice than the 10 main meteorological towers. The large number of sites made regular on-site visits and maintenance impossible; therefore, data collection intervals were reduced from every 10 min to hourly, and the sites were visited biannually rather than monthly. Hardware, software, power, and damage issues resulted in datasets of variable quality and duration. Although most sites produced data records spanning one full winter, duration ranged from 2 to 360 days. Data quality issues primarily revolved around tower destruction or power failure, both are important factors in remote, harsh environments. All corner site data have received an initial quality assurance/quality control (QA/QC) procedure to remove compromised data. Instrument specifications are available by contacting the provider listed on the data archive Web site.

c. North Park eddy covariance system

Two eddy covariance measurements programs were completed. The first program, Flux Over Snow Surfaces, phase I (FLOSS), was completed from 1 December 2001 to 27 March 2002 using an instrumented 20-m scaffold tower. The second program, FLOSS, phase 2 (FLOSS II), was completed with an extended 34-m tower instrumented with additional sensors from 1 December 2002 to 31 March 2003. The tower was located a few hundred meters from the southern edge of the Potter Creek ISA. Only a subset of measurements is available for the first year. (Additional information including instrument specifications and ancillary measurements is available online at <http://www.eol.ucar.edu/rtf/projects/FLOSS/> and at <http://blg.oce.orst.edu/floss/>.)

During the winter of 2001/02, temperature was measured with 20 levels of E-type thermocouples sampled

at 1 Hz at 0.25, 0.5, 1.25, 2.0, 2.75, 3.5, 4.25, 5.0, 5.75, and 6.5 m and every 1.5 m above this level up to 20 m. Fast response data for eddy correlation fluxes and mean winds were collected at seven levels by sonic anemometers for the three components of the wind and sonic (virtual) temperature, four levels of hygrometers for water vapor fluxes, and a single carbon dioxide analyzer. Components of the radiation budget were measured using up- and down-looking pyranometers and pyrgeometers for shortwave and longwave, respectively. Pyrgeometers were also deployed at 4 and 25 m above the ground surface to evaluate longwave radiative flux divergence. Soil measurements include three levels of temperature (0.025, 0.05, and 0.10 m), two levels of moisture (0.05 and 0.10 m), and a heat flux measurement at 0.10 m. A probe capable of measuring thermal properties of the soil was installed to determine heat capacity and thermal conductivity. Barometric pressure and precipitation were also measured. During the winter of 2002/03, mean temperature and relative humidity were measured at eight vertical levels using ventilated temperature and relative humidity instruments built by the Atmospheric Technology Division of the National Center for Atmospheric Research (NCAR).

Eddy correlation measurements were also deployed above a sage community and a dry lake site to assess spatial variability. Temperature, humidity, mean wind speed, and fluxes 2 m above ground level were measured at these two sites, which included four-component radiation sensors and soil sensors. Supplementary sensors for measuring the profiles of soil moisture and temperature were deployed at two sites near the sage tower and at one site near the main tower. Detailed thermocouple profiles within and above the sage community canopy were installed at three locations at the sage site. A micronetwork of 19 slow response thermistors and four 2D sonic anemometers extended south and west from the main tower over an area of $\sim 1 \text{ km}^2$. An additional 11 slow response thermistors spanned an even larger area.

During the 2002/03 winter, three additional soil monitoring stations were installed, one in the sage community under a bush, one in the sage community below bare soil between bushes, and one at a grass site. Measurements included soil moisture, soil water potential, and soil temperature at six depths of 0.05, 0.10, 0.20, 0.30, 0.45, and 0.60 m.

d. North Park airborne meteorological measurements

An extensive dataset of airborne measurements was also acquired using instruments deployed in a Ray-

theon King Air 200T. The Wyoming King Air is operated as a National Science Foundation (NSF) facility, under a joint agreement between NSF and the University of Wyoming. It flew 20 missions between 15 February and 31 March 2003 over the tower site. The primary track traversed North Park, with numerous repeated flight levels between 30 and 100 m above the surface. Analog data were sampled and recorded at 100 Hz. Fast response temperatures and water vapor mixing ratios were collected and recorded.

3. Supplemental meteorological observations

a. U.S. Forest Service observations

All three of the Fraser ISAs are located within the Fraser Experimental Forest, a research watershed monitored by the Rocky Mountain Research Station (RMRS), U.S. Department of Agriculture (USDA) Forest Service, Fort Collins, Colorado. Daily discharge measurements from Lower Fool Creek and East St. Louis Creek gauging stations are available for the 2002 and 2003 water years. Data are archived on the Fraser Experimental Forest Web site (available online at www.fs.fed.us/rm/fraser/data/index.shtml).

b. Natural Resource Conservation Service (NRCS) SNOTEL Observations

The NRCS maintains a network of snowpack telemetry (SNOTEL) sites throughout the seasonally snow-covered portions of the western United States and Alaska, which measure snow water equivalent (SWE), precipitation, and air temperature. Snow depth, soil moisture and soil temperature are measured at select sites. The CLPX small regional study area (SRSA) includes 40 SNOTEL sites. Two sites lay within the Fraser MSA and four lay within the Rabbit Ears MSA. The tower at the SNOTEL site is inside the boundaries of the Buffalo Pass ISA. Data from these sites are offered on a near-real-time basis, and historical data are accessed from the NRCS Water and Climate Center Web site (available online at www.wcc.nrcs.usda.gov).

c. U.S. Geological Survey (USGS) observations

The USGS maintains a research watershed that encompasses a portion of the Walton Creek ISA. Precipitation measurements using an unshielded Belfort rain gauge are on the southern edge of the ISA. Data for the 2003 water year will be available through the National Snow and Ice Data Center's (NSIDC) main CLPX Web site.

TABLE 2. The 1 Jan–31 Mar 2003 mean meteorological conditions by ISA.

ISA	Elevation (m MSL)	Tower environment	Mean 10-m air temp (°C)	Mean 10-m wind speed (m s^{-1})	Mean snow depth (m)	Mean -0.50 m soil temp (°C)
Headquarters	2750	gap	−5.2	0.6	0.80	0.6
St. Louis Creek	2730	canopy	−4.9	0.2	0.81	0.5
Fool Creek	3115	canopy	−6.4	1.1	1.07	0.2
Alpine	3550	open	−9.3	6.6	0.12	−6.5
Potter Creek	2480	open	−4.2	4.8	0.02	−2.2
Illinois River	2475	open	−4.2	4.2	0.05	−1.5
Michigan River	2600	open	−3.9	5.8	0.01	−1.8
Walton Creek	2950	open	−6.5	3.8	1.55	0.9
Spring Creek	2800	open	−5.3	2.1	1.19	0.7
Buffalo Pass	3200	open	−8.3	3.6	2.08	0.9

d. Institute of Arctic and Alpine Research

The Institute of Arctic and Alpine Research (INSTAAR) maintains several alpine and subalpine meteorological and hydrological sites east of the Fraser MSA on Niwot Ridge and in the Green Lakes Valley on the east side of the continental divide. Measured parameters include temperature, relative humidity, radiation, snow depth, and stream discharge. These data are available on the Niwot LTER Web site (available online at <http://culter.colorado.edu/NWT/index.html>).

4. Data availability

The CLPX datasets were released to the public on October 2004 after extensive QA/QC measures. Data can be accessed through the NSIDC Web site (available online at <http://www.nsidc.org/data/clpx/>) or through the Web sites listed above.

5. Examples of data use

MSA and ISA locations were chosen to represent a diverse array of meteorological regimes. Data from the main meteorological towers offer a quantitative means to compare and contrast atmospheric, snowpack, and soil properties at each site. Data presented in Table 2 highlight the unique cryospheric properties found in each MSA and support the study area design in tracking a variety of cold land environments. Mean air temperature between 1 January and 31 March only varied by 6.4°C , showing a strong correlation with elevation. However short-term measurements varied greatly between ISAs and MSAs as a result of synoptic forcing and local effects. Wind speed also showed marked variability when examined over short periods, but relatively close mean values averaged over the winter period with the strongest correlation related to canopy cover. Mean snow depth over the winter varied by two orders of magnitude, with an even greater short-term variability.

Snowpack depth is most closely tied to elevation (orographics) and redistribution by wind. Mean soil temperature over the winter showed a slightly greater between-site range (7.4°C) than air temperature; however, both the short-term mean and variance in air temperature far exceed that of soil. Soil temperature correlates closely with on-site snow depth as a result of the insulating thermal qualities of the snowpack.

The dataset described in this paper as well as the accompanying regional forcing data described by Liston et al. (2008a) and the snow property data described in Elder et al. (2009) were used to develop and test both a meteorological model (MicroMet; Liston and Elder 2006b) and a distributed snow evolution model (SnowModel; Liston and Elder 2006a). MicroMet uses input from point datasets to produce spatially distributed gridded meteorological data capable of driving physically based hydrological models. The CLPX dataset afforded data of sufficient complexity and duration to develop and test the model. The MicroMet-derived data were then used partly to develop, refine, and drive SnowModel, which calculates surface energy exchange, simulates the seasonal evolution of snow depth and water equivalent, and redistributes snow through wind transport. Liston et al. (2008b) further tested these models over larger areas for the CLPX MSAs and also integrated CLPX remotely sensed data (Cline et al. 2009). These integrated efforts demonstrate the value and utility of a comprehensive spatial and temporal meteorological and snowpack dataset.

Meteorological data were also combined with snow pit data (Elder et al. 2009) to model snowpack evolution using the Snow Thermal Model, a one-dimensional snowmelt model (SNTHERM; Jordan 1991). Figure 4 shows the results of the modeling from two significantly different snow environments. The peak snow depth at Buffalo Pass was approximately twice the value seen at Fraser headquarters. The accumulation season was also about two months longer at Buffalo Pass, where peak

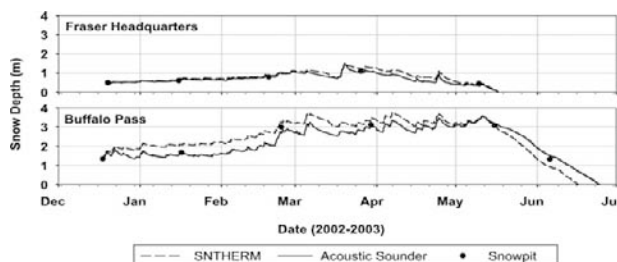


FIG. 4. Seasonal snow depth modeled at the Buffalo Pass and the Fraser headquarters sites. Differences in mean conditions at the two sites during the 2003 field season are detailed in Table 2.

depth was achieved in mid-May; peak depth occurred at Fraser headquarters in mid-March. Figure 4 shows snow depth, not water equivalence. Although depth decreases periodically because of densification, the Buffalo Pass site is actually increasing water equivalence until the mid-May date, the same date that represents near-complete ablation at Fraser headquarters.

The timing, magnitude, and duration of the two snowpacks in this example show differences due to elevation and related energy balance. The Fraser site is 450 m lower, with a mean wintertime temperature 3°C warmer than Buffalo Pass (Table 2). The warmer temperatures lead to earlier melt initiation at Fraser headquarters, a process that stops and starts multiple times because of early season synoptic events. The Buffalo Pass site begins melting at a later date, but once melt season begins in May, there is sufficient energy to lead to rapid and complete snowpack loss as shown in Fig. 4. The differences in energy balance due to site and time of season are clear: at Buffalo Pass, twice as much snow is melted in about two thirds the time as at Fraser headquarters.

In summary, these data are sufficient for snowmelt model development, testing, and calibration and can be coupled with airborne (Cline et al. 2009) and satellite (Davis et al. 2008) remotely sensed data for spatially distributed modeling.

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REFERENCES

- Cline, D., and Coauthors, 2003: Overview of the NASA cold land processes field experiment (CLPX-2002). *Microwave Remote Sensing of the Atmosphere and Environment III*, C. D. Kummerow, J. Jiang, and S. Uratuka, Eds., International Society for Optical Engineering (SPIE Proceedings, Vol. 4894), 361–372.
- , and Coauthors, 2009: NASA Cold Land Processes Experiment (CLPX 2002/03): Airborne remote sensing. *J. Hydrometeorol.*, **10**, 338–346.
- Davis, R. E., and Coauthors, 2008: NASA Cold Land Processes Experiment (CLPX 2002/03): Spaceborne remote sensing. *J. Hydrometeorol.*, **9**, 1427–1433.
- Elder, K., D. Cline, G. E. Liston, and R. Armstrong, 2009: NASA Cold Land Processes Experiment (CLPX 2002/03): Field measurements of snowpack properties and soil moisture. *J. Hydrometeorol.*, **10**, 320–329.
- Hanson, C., 2001: Long-term precipitation database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resour. Res.*, **37**, 2831–2834.
- , D. Marks, and S. Van Vactor, 2001: Long-term climate database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resour. Res.*, **37**, 2839–2841.
- Jordan, R., 1991: A one-dimensional temperature model for a snow cover: Technical documentation for SNTHERM.89. CRREL Special Rep. 91-16, Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, 61 pp.
- Liston, G., and K. Elder, 2006a: A distributed snow-evolution modeling system (SnowModel). *J. Hydrometeorol.*, **7**, 1259–1276.
- , and —, 2006b: A meteorological distribution system for high-resolution terrestrial modeling (MicroMet). *J. Hydrometeorol.*, **7**, 217–234.
- , D. Birkenhauer, C. Hiemstra, D. Cline, and K. Elder, 2008a: NASA Cold Land Processes Experiment (CLPX 2002/03): Atmospheric analyses datasets. *J. Hydrometeorol.*, **9**, 952–956.
- , C. Hiemstra, K. Elder, and D. Cline, 2008b: Mesocell study area snow distributions for the Cold Land Processes Experiment (CLPX). *J. Hydrometeorol.*, **9**, 957–976.
- Williams, M., D. Cline, M. Hartman, and T. Bardsley, 1999: Data for snowmelt model development, calibration and verification at an alpine site, Colorado Front Range. *Water Resour. Res.*, **35**, 3205–3209.