



NASA Cold Land Processes Experiment (CLPX 2002/03): Field Measurements of Snowpack Properties and Soil Moisture

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ABSTRACT

A field measurement program was undertaken as part NASA's Cold Land Processes Experiment (CLPX). Extensive snowpack and soil measurements were taken at field sites in Colorado over four study periods during the two study years (2002 and 2003). Measurements included snow depth, density, temperature, grain type and size, surface wetness, surface roughness, and canopy cover. Soil moisture measurements were made in the near-surface layer in snow pits. Measurements were taken in the Fraser valley, North Park, and Rabbit Ears Pass areas of Colorado. Sites were chosen to gain a wide representation of snowpack types and physiographies typical of seasonally snow-covered regions of the world. The data have been collected with rigorous protocol to ensure consistency and quality, and they have undergone several levels of quality assurance to produce a high-quality spatial dataset for continued cold lands hydrological research. The dataset is archived at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado.

1. Introduction

Snowpack measurements have been taken in North America for nearly 100 years, with the objective of increasing our ability to forecast runoff from snow-covered regions. Point measurements have been the norm, although short transects from snow courses provide a limited representation of the variability of the spatial nature of snow water equivalent (SWE). The snowpack telemetry (SNOTEL) system of the Natural Resources Conservation Service (NRCS) gives regional SWE information in a spatial context but provides no

information on spatial structure below the scale of tens to hundreds of kilometers. Plus, the limited spatial information provided by snow courses and SNOTEL sites is rarely used in any operational hydrological context. Recently, there has been an increased interest in cold regions hydrology, and spatial information on SWE distribution is critical to improving runoff forecasting. Several extensive spatial datasets are available for researchers (e.g., Williams et al. 1999; Marks et al. 2001). The data presented in this study represent a unique contribution in parameters, scale, and resolution and in the particular environment in which they were collected.

The National Aeronautics and Space Administration (NASA) Cold Land Processes Experiment (CLPX) was designed to facilitate significant advances in the field of snow hydrology and the hydrology of cold regions

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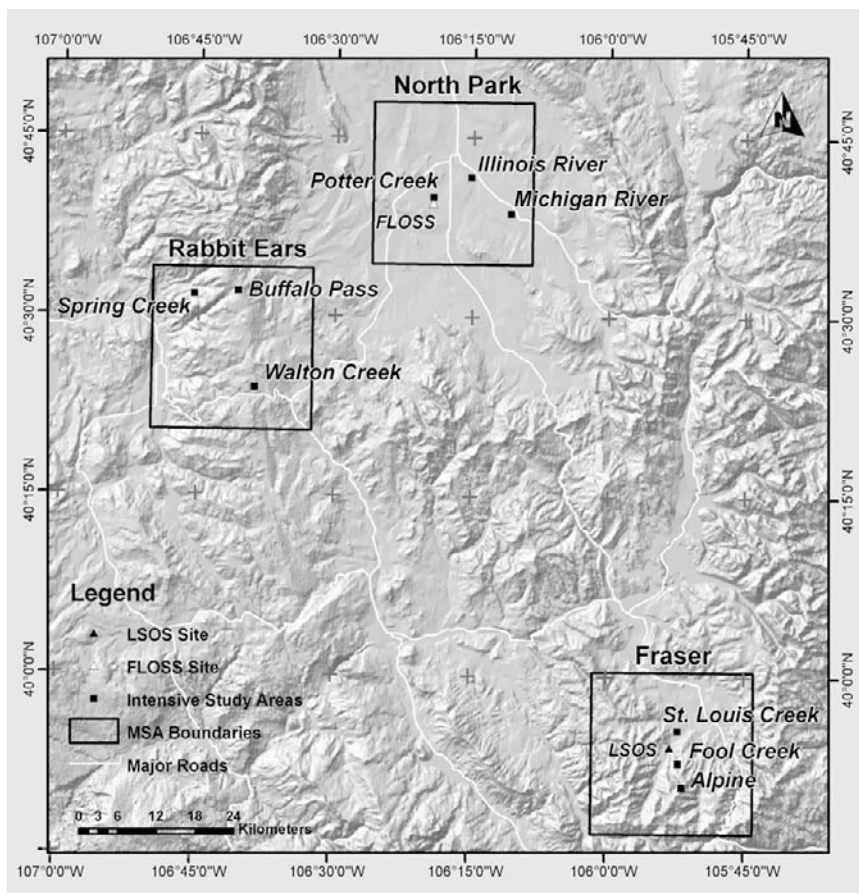


FIG. 1. Field site locations for all three MSAs and all nine ISAs. Note that the entire regional study area is not shown.

(Cline et al. 2003). The experiment was fundamentally designed to refine microwave remote sensing methods. 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. Satellite data were collected during the experiment as well as from existing platforms and missions. The ground-based survey methodology was primarily designed to answer questions of a spatial nature, as mandated by the central theme of the remote sensing research. The field study was carried out with a nested, hierarchical design in which the largest spatial framework was the large regional study area ($4.5^{\circ} \times 3.5^{\circ}$; 38.5° – 42° N, 104° – 108.5° W; Cline et al. 2003). The large regional study area was further divided into three mesoscale study areas (MSAs), each $25 \text{ km} \times 25 \text{ km}$, and included Fraser, North Park, and Rabbit Ears. The three MSAs each contained three intensive study areas (ISAs), each $1 \text{ km} \times 1 \text{ km}$ (Fig. 1). The Fraser MSA contained the St. Louis, Fool Creek, and Alpine ISAs. The North Park MSA contained the Michigan River,

Illinois River, and Potter Creek ISAs. The Rabbit Ears MSA contained the Walton Creek, Spring Creek, and Buffalo Pass ISAs.

Field measurements were divided into two main categories: transect and snow pit measurements. Transect data included snow depths and related measurements, as detailed below. Snow pits were excavated at fixed locations and related measurements were made, also detailed below. The field effort has produced an extensive legacy dataset that can be used to answer current and future questions related to cold regions remote sensing and hydrological processes.

2. Methods

a. Schedule

Ground-based sampling took place during two periods over two years, giving a total of four intensive observation periods (IOPs). The two periods (late February and late March) were repeated during the two study

TABLE 1. Schedule of CLPX activities, measurements and locations.

IOP	Date	Activity	MSA
IOP1	17 Feb 2002	Safety training	Fraser
	18 Feb 2002	Protocol training	Fraser
	19 Feb 2002	Depth	Fraser
	20 Feb 2002	Snow pit, remaining depth locations	Fraser
	21 Feb 2002	Depth and snow pit	North Park
	22 Feb 2002	MSA snow pit, remaining ISA depth and snow pit	North Park
	23 Feb 2002	Depth	Rabbit Ears
	24 Feb 2002	Snow pit, remaining depth locations	Rabbit Ears
	24 Mar 2002	Protocol training	Fraser
	25 Mar 2002	Depth	Fraser
IOP2	26 Mar 2002	Snow pit, remaining depth locations	Fraser
	27 Mar 2002	Depth and snow pit	North Park
	28 Mar 2002	MSA snow pit, remaining ISA depth and snow pit	North Park
	29 Mar 2002	Depth	Rabbit Ears
	30 Mar 2002	Snow pit, remaining depth locations	Rabbit Ears
IOP3	17 Feb 2003	Safety training	Fraser
	18 Feb 2003	Protocol training	Fraser
	19 Feb 2003	Depth	Fraser
	20 Feb 2003	Snow pit, remaining depth locations	Fraser
	21 Feb 2003	Depth and snow pit	North Park
	22 Feb 2003	MSA snow pit	North Park
	23 Feb 2003	Weather day—no samples collected	
	24 Feb 2003	Depth	Rabbit Ears
	25 Feb 2003	Snow pit, remaining depth locations	Rabbit Ears
	24 Mar 2003	Protocol training	Fraser
IOP4	25 Mar 2003	Depth	Fraser
	26 Mar 2003	Snow pit, remaining depth locations	Fraser
	27 Mar 2003	Depth and snow pit	North Park
	28 Mar 2003	Depth and snow pit, MSA snow pit	North Park
	29 Mar 2003	Depth	Rabbit Ears
	30 Mar 2003	Snow pit, remaining depth locations	Rabbit Ears

years (2002 and 2003). IOP1 was conducted from 17 to 24 February 2002, IOP2 from 24 to 30 March 2002, IOP3 from 17 to 25 February 2003, and IOP4 from 25 March to 1 April 2003. Dates, specific activities, and locations can be found in Table 1. February was chosen to ensure cold snowpacks, so the presence of liquid water in the snow would not complicate the microwave remote sensing. The March dates were chosen to obtain samples during the transition from a cold snowpack to a melting snowpack, so the effects of liquid water in the snowpack on the microwave spectrum could be studied.

b. Transect data

Each ISA was divided into one hundred 1-ha cells ($100 \text{ m} \times 100 \text{ m}$). A random point within each cell was selected as a transect origin. A transect interval was randomly selected from 5, 10, 15, 20, or 25-m lengths, and a random orientation in one of the cardinal directions was selected. These intervals and the frequency of selection were designed to obtain an adequate number of pairs through a range of lagged spatial scales for

analyses and modeling. Transects were each five points with three points in the first direction selected, followed by a second randomly selected direction 90° to the right or to the left of the original vector. If either the first or the second direction resulted in the transect leaving the 100 m^2 cell, then a second direction was randomly selected and the procedure was repeated. This sampling scheme resulted in 100 cells with five transect points within each cell in an L-shaped profile, with transects oriented in all four cardinal directions at variable transect intervals of 5, 10, 15, 20, and 25 m. In the second year of sampling (IOP3 and IOP4), 1-m interval transects were added to the sampling scheme to gain insight into finer spatial scales than the 5-m interval measured in IOP1 and IOP2. One existing transect from each quadrant of the ISA ($250 \text{ m} \times 250 \text{ m}$ cells) was randomly selected, and these transects were sampled at 1-m intervals regardless of the original transect interval. Identical relative transect locations were used for all nine ISAs and each IOP. Figure 2 shows the relative locations of all the sample points for the snow depth survey transects within a single ISA.

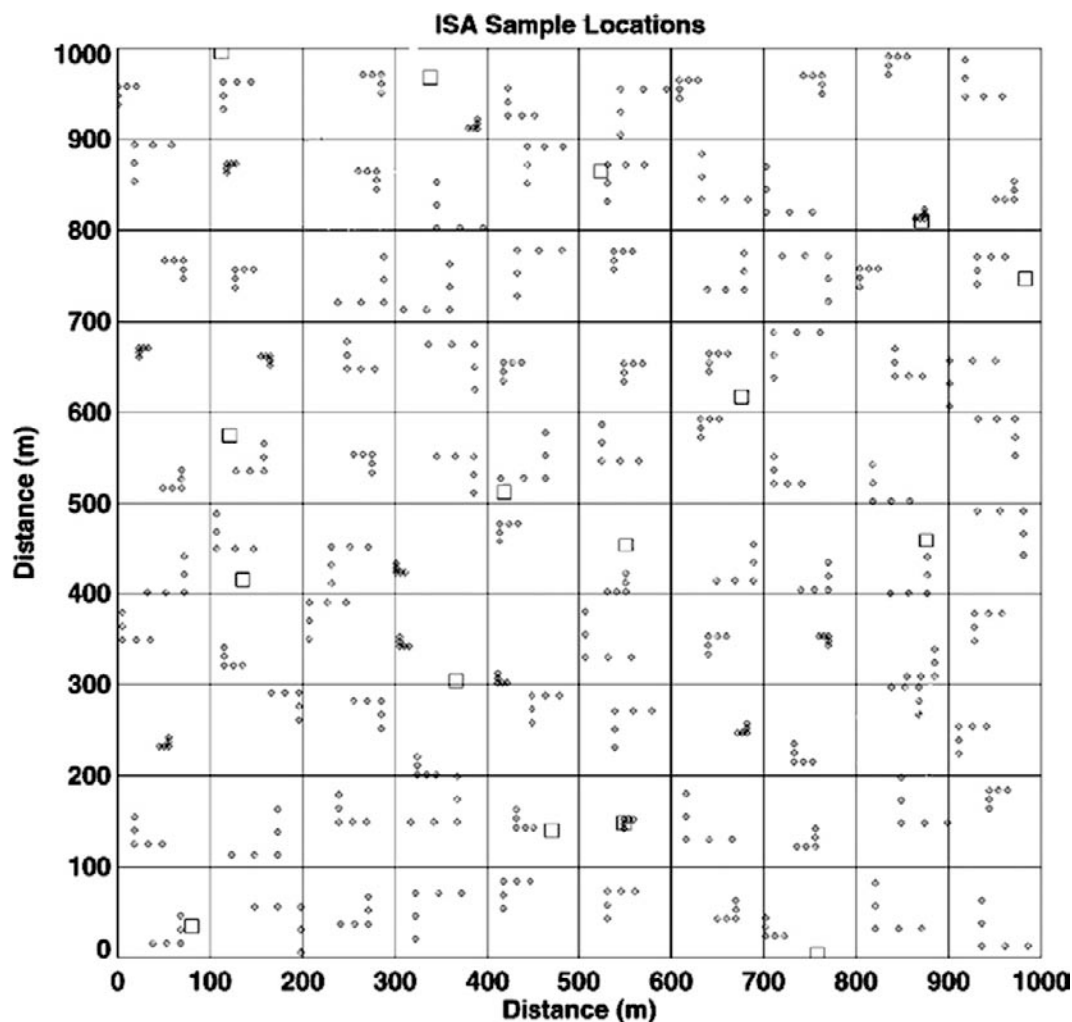


FIG. 2. Relative locations of depth transects (diamonds) and snow pits (squares) for all ISAs.

Transect starting points were located before snowfall with GPS, and each starting point was marked with a metal T-post, or acrylonitrile butadiene styrene (ABS) or polyvinyl chloride (PVC) tubing, or surveyors tape. Teams of 2–4 people sampled the transects. Field books were provided to each team with the transect starting point universal transverse Mercator (UTM) coordinates, the direction, and the distance to subsequent points as well as their UTM locations and a description of the location with geographical features noted when the points were originally laid out. During the surveys, transect starting points were located using maps, compasses, and GPS. A compass was then used to find the orientation of the first and second legs of the L-shaped transects. Distances between sampling points on the transects were measured with the snow depth probes. In each transect snow depth, snow surface wetness, snow surface roughness, and canopy were measured.

1) SNOW DEPTH

Snow depth was measured with aluminum probes with 0.01-m graduations. Probe sections could be linked together in a series to obtain a probe length capable of reaching the snow/ground interface at all of the field sites. Snowpack depths were recorded to the nearest 0.01 m. Snow depths were taken orthogonally to a theoretical flat earth surface, not normal to the local slope.

2) SURFACE WETNESS

An observation of surface wetness was made at the initial point of each transect. Values were used from the internal classification (Colbeck et al. 1990) using dry, moist, wet, very wet, and slush based on a grab sample from the snow surface. The description is qualitative and somewhat subjective. Time constraints and cost precluded a more quantitative approach.

3) SURFACE ROUGHNESS

Snow surface roughness was recorded at the initial point of each transect. The surface roughness samplers consisted of a 1 m \times 0.25 m \times 6.4 mm black ABS plastic board. The board was inserted vertically along the long axis into the snow surface and photographed obliquely with a digital camera. Then software calculated the surface roughness correlation length based on the snow surface profile resolved against the black background. If the first point was snow free, the observation was made at the first point with snow cover sufficient to cover the length of the base of the roughness board. If the entire 1-m length of the board could not be inserted into the snow, then the photograph was not taken even if a depth was recorded.

4) CANOPY

At each transect point, elementary canopy characteristics were recorded if the point fell directly under the canopy in forested areas. Recorded characteristics included Yes/No for presence of canopy, and if yes, then snow or snow free. Canopies were only considered to hold snow if it were a significant amount; light dusting of snow in the canopy was considered snow free. The motivation was to record snow if it was thought to significantly affect remotely sensed imagery.

Canopy in unforested areas such as North Park was defined as grass, shrub, or willow if the canopy extended above the snowpack surface at the point of depth measurement. In addition to canopy type, the height of the top of the canopy was also recorded with snowpack depth. Subtracting the latter from the canopy height allows for the calculation of vegetation height above the snow surface. Canopy height was only measured in North Park, where the probes could be used for direct measurement. No estimate of canopy height was taken in forested areas because of the difficulty in gaining an accurate value with the available equipment.

c. Snow pit data

Each ISA was divided into four 250 m \times 250 m quadrants. Four locations in each quadrant were randomly located for a total of 16 snow pits sites in each ISA. Pit locations were located with GPS and marked before snowfall with a metal T-post, or ABS or PVC tubing. Each snow pit site was sampled 2 times during each field season. To ensure that undisturbed snow was sampled each time, a strict protocol for actual pit location was followed. On flat sites, the first snow pit was located on the south side of the pit marker, and the second pit was located to the north of the marker. On sloped locations, the first pit was located on the down-

slope side of the marker, and the subsequent pit was excavated on the upslope side of the marker. Shaded pit walls were sampled to minimize solar influences on the measurements. Pits were backfilled to minimize influences to the undisturbed surrounding snowpack and for the safety of recreationists. Figure 1 shows the relative locations of the 16 snow pits in each ISA.

An additional snow pit dataset was collected at all 10 main meteorological stations. Each station (Elder et al. 2009) was visited on a monthly basis (approximately) from the beginning of the accumulation season to the end of the melt season. The full protocol for the snow pit measurements, detailed below, was followed at each site. These data provide a record of the snowpack evolution at the meteorological sites, allowing coupled modeling with the meteorological and detailed snowpack data at the different sites.

1) SNOW DENSITY

Snow density was measured with a wedge-shaped sampler with a 1-L volume. Samples were extracted from the vertical pit wall and weighed in the sampler on a digital top-loading scale with 1-g accuracy. Measurements were made in 0.10-m increments from the snow surface to the snow/ground interface. Ground roughness and vegetation usually preclude a measurement at the exact snowpack base. Two density profiles were recorded side by side except in the rare case when time and safety limited sampling efforts.

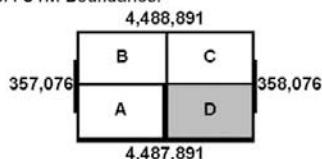
In the shallow snowpacks found above treeline at the Fraser Alpine site and at all of the North Park sites, an alternative sampling method was necessary for measuring density. This technique includes the following steps: 1) if snow depths were less than 0.15 m or if an adequate sample could not be obtained with the 1-L sampler, then a tube sampler was employed; 2) a snow, ice, and permafrost research establishment (SIPRE)-type 0.5-L tube was inserted vertically into the existing snowpack to the snowpack base, then a spatula was inserted horizontally under the tube to isolate and contain the sample; and 3) the sample was removed and placed on the digital scale, and the weight and total depth of the sample were recorded. This technique was repeated three times at each site in an attempt to account for local variability. Density was calculated based on the weight and volume of each sample after leaving the field.

2) SNOW TEMPERATURE

Temperature was measured at the snow surface and at 0.10-m increments to the base of the snowpack. The temperature at the snow/ground interface was also recorded. A bimetal analog dial stem thermometer with a

MSA: **RABBIT EARS**
 ISA: **BUFFALO PASS**
 Sector: **DELTA**
 Surveyed By: Liston
 Date: 20020223

ISA UTM Boundaries:



Transects 21 to 24

DIRECTIONS:

Depth: Record Depth to nearest centimeter (cm)
Wetness: Dry (D), Moist (M), Wet (W), Very Wet (VW)
Roughness: Photo Taken? Yes (Y) or No (N)
 (1 Photo per Transect)
Canopy: Point underneath canopy?
 Yes/Coniferous (C), Yes/Deciduous (D) or No (N)

		UTM - E	UTM - N			
Cell	Start Location (UTM):	358,012	4,487,954			
D21	Description Pole - E of small clump of trees, S of tower					
	Start Time:	1035MST				
	Interval (m):	25	Direction: S then E			
Pt. #	Point Name	Move	Depth (cm)	Wet	Rough	Can
1	RBD21.1	Start	97	m	y	n
2	RBD21.2	25m S	168	m	n	n
3	RBD21.3	25m S	188	m	n	n
4	RBD21.4	25m E	185	m	n	n
5	RBD21.5	25m E	123	m	n	n
Comments:						

		UTM - E	UTM - N			
Cell	Start Location (UTM):	357,987	4,488,115			
D23	Description Pole - Near trees, just N of North tower					
Start Time:		1015MST				
Interval (m):		15	Direction: N then E			
Pt. #	Point Name	Move	Depth (cm)	Wet	Rough	Can
1	RBD23.1	Start	139	d	y	c
2	RBD23.2	15m N	180	d	n	n
3	RBD23.3	15m N	208	d	n	n
4	RBD23.4	15m E	231	d	n	n
5	RBD23.5	15m E	244	d	n	n
Comments:						

		UTM - E	UTM - N			
Cell	Start Location (UTM):	358,020	4,488,055			
D22	Description	Pole - Open, ~20m E of South tower				
	Start Time:	1025MST				
	Interval (m):	10	Direction: N then E			
Pt. #	Point Name	Move	Depth (cm)	Wet	Rough	Can
1	RBD22.1	Start	184	m	y	n
2	RBD22.2	10m N	29	m	n	n
3	RBD22.3	10m N	159	m	n	c
4	RBD22.4	10m E	290	m	n	n
5	RBD22.5	10m E	311	m	n	n
Comments: #2 wind scour area. #4 tree drift. #5 tree drift.						

		UTM - E	UTM - N			
Cell	Start Location (UTM):	358,004	4,488,239			
D24	Description Pole - Clump of trees just N of gully					
	Start Time: 0920MST					
	Interval (m): 15	Direction: N then E				
Pt. #	Point Name	Move	Depth (cm)	Wet	Rough	Can
1	RBD24.1	Start	169	d	y	n
2	RBD24.2	15m N	184	d	n	n
3	RBD24.3	15m N	144	d	n	n
4	RBD24.4	15m E	153	d	n	n
5	RBD24.5	15m E	177	d	n	n
Comments:						

FIG. 3. Example field notes from depth survey collected 23 Feb 2002 at Buffalo Pass ISA.

125-mm stem and a 45-mm diameter face was used. Temperatures were recorded to the nearest whole degree. Surface temperatures were shaded with a shovel blade to reduce solar loading to the thermometer stem. Thermometers were calibrated periodically in an ice bath throughout the experiment. The precision for the thermometers was 1°C, and the accuracy was $\pm 1^\circ\text{C}$.

3) SNOW STRATIGRAPHY

Stratigraphy was recorded for major layers in the snowpack. Vertical delineation of the major layers was determined by subjective methods including grain type and size, snow strength, and boundaries such as ice lenses and crusts. Both grain type and size were recorded for major layers; they were determined using a 8×30 pocket microscope with a graduated reticule with 0.1-mm graduations. Grain type was limited to new snow (N), rounded or equilibrium snow (R), faceted or kinetic snow (F), or mixed rounds and facets (M). Grain size was recorded for three representative grains from each layer. Field workers were instructed to not look for the largest or smallest grains in a sample but to select a grain representative of the large and small grains as well as the mean. It is recognized that

there is a high degree of subjectivity in this measurement scheme but time, logistics, and cost precluded more robust sampling methods. The *a* and *b* axes of a small, medium, and large grain out of each layer were recorded to the nearest 0.1 mm.

4) SOIL MOISTURE

Two soil cores were taken at the base of each snow pit. An attempt was made to sample the top 0.20 m of soil but rocks, ice, and other factors resulted in variable achievable depths. The actual depth of the core was recorded in each case. Samples were placed in sealed plastic containers and labeled with the date and location. Gravimetric soil moisture was determined in the laboratory after drying in ovens; percent moisture was calculated by (dry weight)/(wet weight - dry weight). The state of the soil (frozen or unfrozen) was recorded for each pit.

d. Motor tours

The North Park MSA provided opportunities for sampling the entire 25 km \times 25 km area not afforded by the other two MSAs as a result of terrain and deep

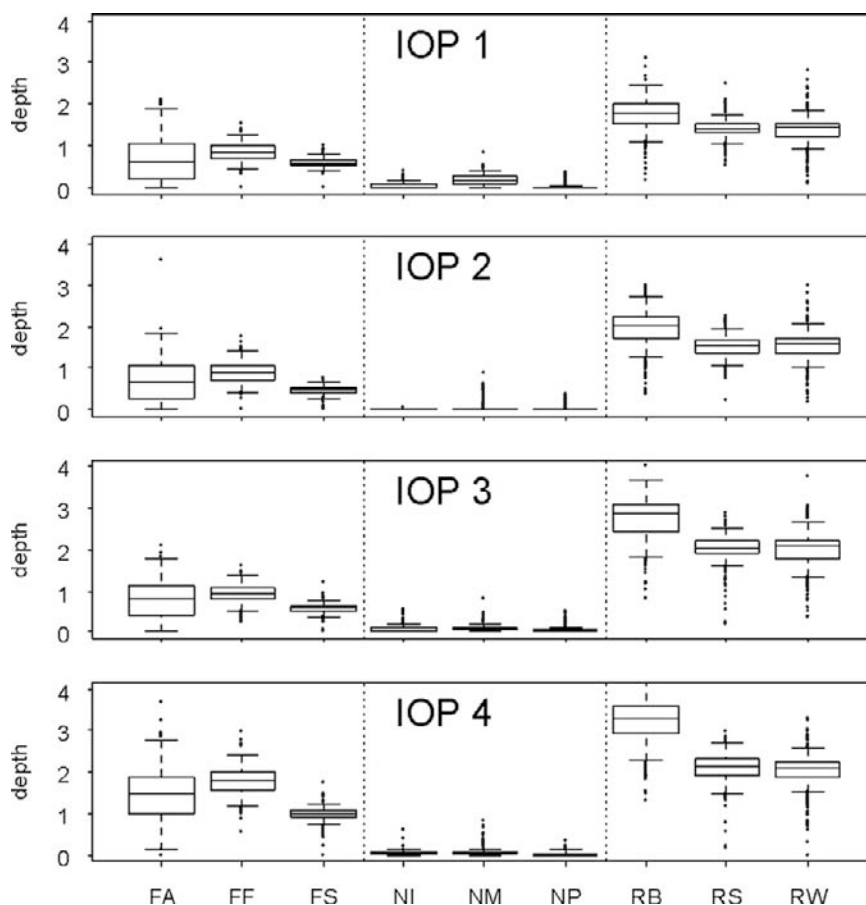


FIG. 5. Snow depth (m) measurements by ISA for all IOPs: FA = Fraser, Alpine; FF = Fraser, Fool Creek; FS = Fraser, St. Louis Creek; NI = North Park, Illinois River; NM = North Park, Michigan River; NP = North Park, Potter Creek; RB = Rabbit Ears, Buffalo Pass; RS = Rabbit Ears, Spring Creek; RW = Rabbit Ears, Walton Creek. Values are depths from individual sampling points on transects ($n = 500+$, in most cases). Vertical full-length dotted lines separate MSAs (Fraser, North Park, and Rabbit Ears). Horizontal lines in the boxes represent median depths. Upper and lower bounds of the boxes represent the inner quartile ranges. The staples at the whisker ends represent twice the inner quartile ranges. The circles represent outliers falling outside twice the inner quartile ranges. All outliers are shown. Note that small sample sizes at NI and NP during IOP 2 are a result of the lack of snow cover at snow pit sites during the sampling period.

Figures 3 and 4 show examples of the field books for the depth transects and snow pits, respectively. A slightly modified version of the snow pit data sheet was used for the shallow sites where the SIPRE density samplers were used.

3. Results

a. Synopsis of the field efforts

Weather and safety considerations did not allow 100% success in the planned data collection. However, the objectives were very nearly met in most cases. Extreme weather during IOP3 and IOP4 made travel in

deep new snow extremely arduous and difficult. With new snow depths exceeding 1 m, safety concerns were critical and travel times between sample points increased dramatically, thereby limiting the quantity of data that could be collected. An examination of datasets and metadata at National Snow and Ice Data Center (NSIDC) indicate actual data acquired.

b. Data processing and storage

Field books were collected from the survey teams each day as they returned from the field. They were immediately examined for quality, and the data was entered into prescribed data formats on computers by

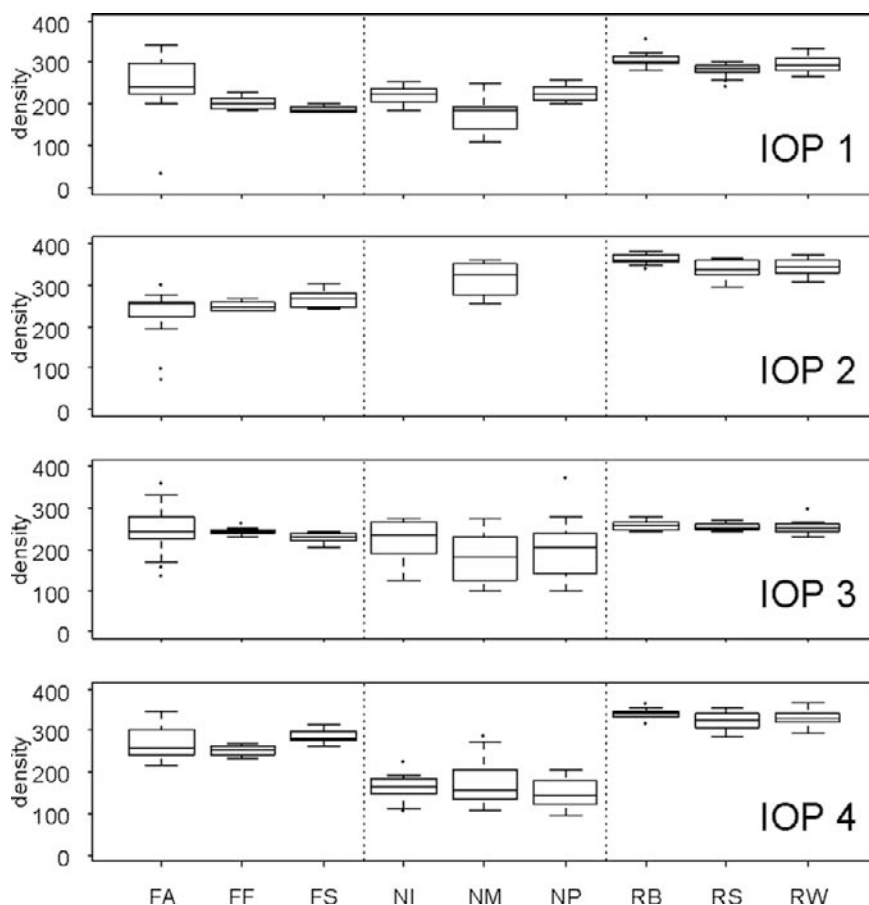


FIG. 6. Mean snow density (kg m^{-3}) measurements by ISA for all IOPs. Values are mean densities from full pit profiles ($n = 16$, in most cases). Refer to Fig. 5 for definition of acronyms. Note that missing data at NI and NP during IOP 2 are a result of the lack of snow cover at snow pit sites during the sampling period. Refer to Fig. 5 for an explanation of the box-and-whisker plot details.

the data team. Survey teams were queried that evening or the following morning for anomalies to reduce problems as a result of memory loss. The entire dataset was then reviewed by the data team and project scientists for quality control before a final dataset was produced. The data are stored in a data archive at the NSIDC in Boulder, Colorado (available online at nsidc.org/data/clpx).

c. Data analyses

Preliminary analyses of snow density, snow depth, and snow water equivalent show that one of the objectives of the study, to characterize different snow climates, was clearly met. Figure 5 shows a box and whisker plot of snow depths measured during all IOPs at all ISA sites. The results clearly show that a wide range of snow depths and snow accumulation environments were sampled. Substantial variability exists between

MSAs (Fraser, North Park, and Rabbit Ears) and within MSAs between individual ISAs. There were also significant differences in snow depths between IOPs. Figure 6 shows a box-and-whisker plot of mean snow densities sampled in all snow pits during all IOPs at all ISA sites. Density exhibits variability between MSAs and between ISAs. The greatest variability occurs with the North Park MSA where snow cover is shallow and ephemeral. The greatest densities and least variability occur in the deep snowpacks of the Rabbit Ears MSA where persistent snow cover with a heavy overburden promotes densification.

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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. Hydrometeor.*, **10**, 338–346.
- Colbeck, S., E. Akitaya, R. Armstrong, H. Gubler, J. Lafeuille, K. Lied, D. McClung, and E. Morris, 1990: The international classification for seasonal snow on the ground. International Association of Scientific Hydrology, 37 pp.
- Elder, K., D. Cline, A. Goodbody, P. Houser, G. E. Liston, L. Mahrt, and N. Rutter, 2009: NASA Cold Land Processes Experiment (CLPX 2002/03): Ground-based and near-surface meteorological observations. *J. Hydrometeor.*, **10**, 330–337.
- Marks, D., K. Cooley, D. Robertson, and A. Winstral, 2001: Long-term snow database, Reynolds Creek Experimental Watershed, Idaho, United States. *Water Resour. Res.*, **37**, 2835–2838.
- 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.