Putting the Capital "A" in CoCoRaHS: An Experimental Program to Measure Albedo using the Community Collaborative Rain, Hail, and Snow (CoCoRaHS) Network

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ABSTRACT

The Community Collaborative Rain, Hail, and Snow (CoCoRaHS) Network, is a community-based network of weather observers and the largest provider of daily precipitation observations in the United States (US). In this study, we embrace the CoCoRaHS mission to use low-cost measurement tools, provide training and education, and utilize an interactive website to create the first volunteer snow albedo network to collect high quality albedo data for research and education applications. We trained a sub-set of eighteen CoCoRaHS observers in the state of New Hampshire to collect albedo, snow depth, and snow density between 23-Nov-2011 and 15-Mar-2012. At less than $700 per observer, CoCoRAHS albedo data measured using an Apogee MP-200 pyranometer fall within ± 0.05 of albedo values collected from a Kipp and Zonen CMA6 at local solar noon. CoCoRaHS albedo values range from 0.99 for fresh snow to 0.34 for shallow, aged snow. Snow-free albedo ranges from 0.09 to 0.39, depending on underlying ground cover. In the 2011/2012 dataset, albedo increases logarithmically with snow depth and decreases linearly with snow density. The latter relationship is inferred to be a proxy for increasing snow grain size as snowpack ages and compacts, supported by spectral albedo measurements collected with an ASD FieldSpec4 spectrometer.

Keywords: albedo, snow, citizen science.

INTRODUCTION

Surface albedo, the ratio of upwelling to downwelling solar radiation, has been identified by the Intergovernmental Panel on Climate Change as the only anthropogenic radiative forcing to have a local to regional effect on climate (Forster et al., 2007). Just over half of respondents in two independent surveys in the United States demonstrate scientific understanding of the impact albedo has on climate (Reynolds et al., 2010; Leiserowitz et al., 2010), and no increase in public understanding of albedo has occurred since 1992 (Reynolds et al., 2010).

The Community Collaborative Rain Hail and Snow (CoCoRaHS) Network represents one of the largest citizen scientist initiatives in the United States to increase both the spatial density of daily precipitation measurements and the public understanding of climate and weather. Here, we embrace the CoCoRaHS mission to use low-cost measurement tools, provide training and education, and utilize an interactive website to collect, record, and communicate high quality daily

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albedo measurements for research and education applications. The emphasis of our initiative is to relate changes in surface albedo (especially over snow) to land cover during winter in New Hampshire.

Climate modeling studies reveal that changes in land cover in the mid-latitudes have cooled climate by 0.06°C to 2°C, primarily through increases in surface albedo (Davin and de Noblet-Ducoudé, 2010; Kvalevåg et al., 2010; Strengers et al., 2010; Bonan, 2008; Betts, 2001). The coarse resolution of global climate models and annualized temperature trends used in these studies makes it difficult to detect local patterns in land cover change that are in opposition to global or latitudinally averaged trends. For example, most of the northern hemisphere mid-latitude deforested area has remained deforested through present day (Pitman et al., 2009). The northeastern United States, however, has undergone substantial reforestation since peak deforestation in 1870 (Foster et al., 2008). In New Hampshire, forest cover dipped below 50% at peak deforestation and has since reforested to become the second most-forested state in the US with over 80% forest cover. Similar land cover trends are found throughout the northeastern United States.

The land cover history in the northeastern US is inverse to hemispheric trends; it follows that the sign and magnitude of climate trends in New Hampshire and the northeastern US could differ substantially to the global to continental cooling trends identified in previous modeling studies. Winter temperatures in the Northeastern US have warmed 0.12°C/decade over the period 1900-1999 (Hayhoe et al., 2007), and an estimated 1.5°C (0.1°C/decade) of warming has occurred since 1850 (Hodgkins et al., 2002). As winter temperatures have warmed, Northeastern US winter snowfall has been decreasing moderately between 0% and 0.2% per year over the period 1900/1901 to 2006/2007 (Kunkel et al., 2009). Over the North American continent between 1915-2010, March snow cover extent (SCE) decreased -0.22×10^6 km per 100 yr and April SCE decreased -0.83×10^6 km per 100 yr, respectively (Brown and Robinson, 2010).

In the heavily forested northeastern US, local daily temperature depressions of 5°C to 6°C during periods of snow cover are identified in climate station records, with larger temperature depressions occurring away from the coast and during the mid-winter months (Leathers et al., 1995). However, all climate stations used in the study are situated in non-forested areas, so the impact of snow cover on climate in forested areas of the northeast US remains unclear. Annually average surface air temperatures are $+ 0.85 \pm 0.44$°C cooler at climate stations located in deforested landscapes compared to tower measurements made over nearby forested lands at latitudes north of 45°N, and the temperature difference is particularly warmer at night (Lee et al., 2011). A study of surface temperature and radiation data collected in deforested areas between 1963 and 1985 found that average maximum and minimum air temperatures in January were 8.6°C colder on days with snow cover greater than 10 cm compared to snow-free days (Baker et al., 1992). In central North America, temperature depressions in winter over grasslands range from 2.6°C to 4.5°C in minimum and maximum temperature, while areas of decreased maximum albedo, indicative of denser forest cover, have temperature depressions ranging from 1°C to 1.5°C (Mote, 2008). A focus on smaller regions is therefore necessary to better understand the local climate response to land cover change specific to those regions.

Using a network of volunteer citizen scientists and tower-based albedo measurements, this study aims to identify relationships amongst albedo, snow depth, and snow density. To our knowledge, the CoCoRaHS Albedo pilot project in New Hampshire is the first volunteer albedo network in the US. In addition to educating our citizen scientists about the climate impact of albedo, this research also attempts to answer the following questions: (1) how does albedo relate to snow depth and snow density and (2) how does underlying ground cover affect snow albedo relationships?

METHODS AND INSTRUMENTATION

CoCoRAHS Volunteers

Eighteen volunteers across the state of New Hampshire were invited to participate in the first field season of data collection (Figure 1; Table 1). Nearly all of the field sites are characterized as mowed grass and lawn, with the exceptions of NH-MR-06 best characterized as bare soil, and NH-GR-11 classified as a wooden observation deck on a rooftop at Plymouth State University. CoCoRAHS volunteers are equipped with a customized toolkit to measure snow depth, snow density, and surface albedo (Figure 1). The kit includes a yardstick, a spatula, a 60.96 cm (2 ft) aluminum snow tube, a 121.92 cm (4 ft) snow tube, a CCi HS digital hanging scale, an Apogee MP-200 pyranometer mounted to a 91.44-cm rectangular aluminum boom, and a field notebook, for a total cost of less than $700 per observer.
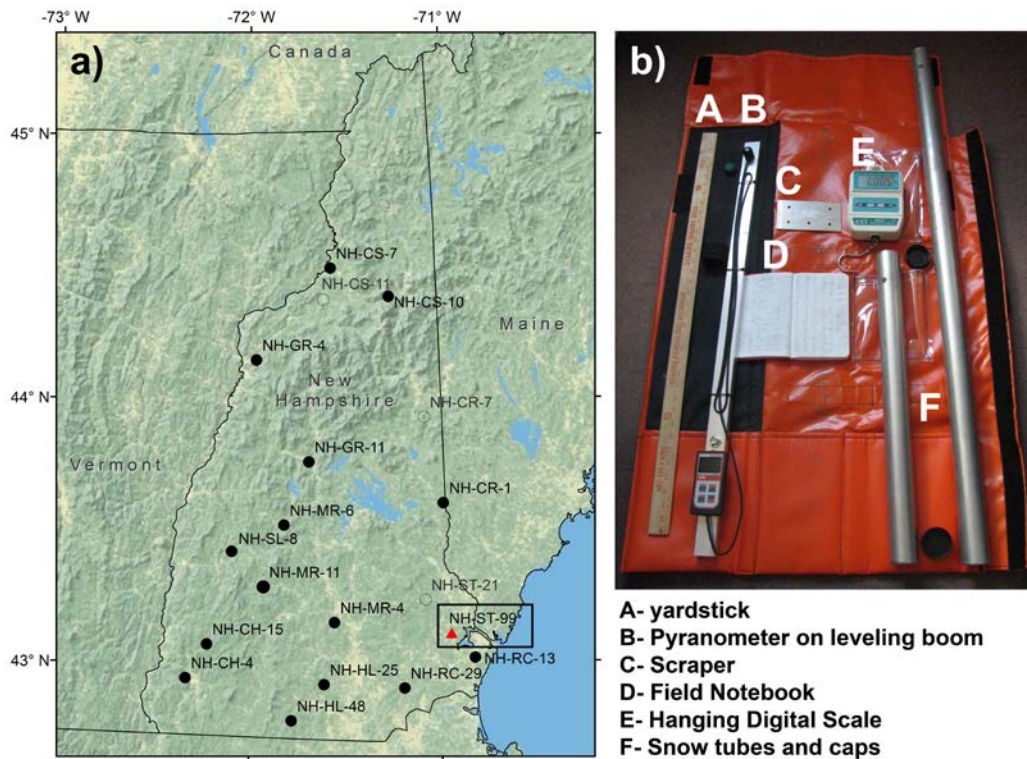

Figure 1. The (a) CoCoRAHS albedo observer network and (b) CoCoRAHS instrument kit distributed to volunteers for the 2011/2012 winter sampling season, 23-Nov-2011 through 15-Mar-2012.

The Apogee MP-200 is a silicon cell pyranometer calibrated to a Kipp and Zonen CM 21 pyranometer at the manufacturer's facility to measure total shortwave radiation in the range 285-2800 nm, with a sensitivity of 5.0 W m^{-2} per mV and absolute accuracy of $\pm$ 5%. Output is displayed on the meter in whole W m^{-2}. The cosine response of the MP-200 is $\pm$ 1% at 45° solar zenith angle and $\pm$ 5% at 75° solar zenith angle. Solar zenith angles within the CoCoRaHS Albedo Network ranged from a maximum of 67.9° on 22-Dec-2011 at the northernmost site in Lancaster, NH (NH-CS-7) to 44.8° on 15-Mar-2012 at the southernmost site (NH-HL-48). Apogee Instruments Co., does not calibrate the MP-200 for reflected radiation. To address this, the authors calibrated reflected radiation and albedo for one pair of MP-200's to a Kipp and Zonen CMA 6 albedometer in the range of 285-2800 nm over the period 4-Jan-2012 to 15-Feb-2011 (see *Calibration of Apogee MP-200 Pyranometer*).

Table 1. Albedo statistics for CoCoRaHS volunteer observer stations for the 2011/2012 sampling season, 23-Nov-2011 through 15-Mar-2012.

Station ID	Lat	Lon	Total # obs	# obs	Mean	Std	# obs	Mean	Std	Surface Type
				Snow-free Albedo			Snow-covered Albedo			
NH-CH-04	42.9395	−72.3284	12	1	0.35	0.00	11	0.69	0.19	grass lawn
NH-CH-15	43.0676	−72.2187	57	36	0.28	0.04	21	0.61	0.12	grass lawn
NH-CR-01	43.6037	−70.9867	77	19	0.28	0.12	58	0.64	0.10	grass lawn
NH-CR-07	43.9295	−71.0841	0	0	--	--	0	--	--	grass lawn
NH-CS-07	44.4961	−71.5764	87	3	0.29	0.05	76	0.83	0.12	grass lawn
NH-CS-10	44.3882	−71.2695	79	1	0.59	0.00	3	0.94	0.02	grass lawn
NH-CS-11	44.3764	−71.6132	4	0	--	--	86	0.74	0.14	grass lawn
NH-GR-04	44.1467	−71.9650	24	25	0.24	0.06	43	0.70	0.17	grass lawn
NH-GR-11	43.7603	−71.6889	68	6	0.30	0.03	18	0.78	0.10	wooden deck
NH-HL-25	42.9141	−71.6102	55	33	0.26	0.04	22	0.67	0.15	grass lawn
NH-HL-48	42.7767	−71.7799	54	30	0.32	0.14	24	0.77	0.10	grass lawn
NH-MR-04	43.1499	−71.5565	85	26	0.33	0.10	39	0.71	0.17	grass lawn
NH-MR-06	43.5200	−71.8190	95	5	0.21	0.06	80	0.62	0.17	bare soil
NH-MR-11	43.2849	−71.9253	71	21	0.21	0.06	74	0.74	0.19	grass lawn
NH-RC-13	43.0159	−70.8272	10	1	0.27	0.00	9	0.74	0.10	grass lawn
NH-RC-29	42.9015	−71.1927	22	1	0.27	0.00	21	0.63	0.18	grass lawn
NH-SL-08	43.4201	−72.0910	67	13	0.29	0.10	53	0.71	0.18	grass lawn
NH-ST-21	43.2356	−71.0823	0	0	--	--	0	--	--	grass lawn
NH-ST-99	43.1088	−70.9486	52	18	0.34	0.03	34	0.67	0.22	pasture

Volunteers were instructed to collect daily albedo measurements within ± 1 hour of local solar noon between 23-Nov-2011 and 15-Mar-2012. Solar noon for each location was determined using the National Oceanic and Atmospheric Administration (NOAA) Solar Noon Calculator (http://www.esrl.noaa.gov/gmd/grad/solcalc/). Downwelling solar radiation measurements are made by pointing the boom outward from the hip at the sun with the optic pointing upward, using bubble levels mounted near the hip to ensure the optic was level. The boom is then rotated 180° such that the optic pointed downward to collect upwelling (reflected) radiation. Three downwelling and upwelling paired measurements are taken at or around local solar noon and surface albedo is calculated as the sum of the upwelling values divided by the sum of the incoming values.

Snow density measurements are taken by inserting the empty aluminum snow tube vertically into the snow pack. A spatula is used to scrape out a snow pit to characterize the vertical profile of the snowpack. The yardstick is placed next to the tube to determine the depth, measured to the nearest 1.27 cm (0.5 in.). The spatula is then slid under the base of the tube and the snow tube is capped and weighed using the digital hanging scale. The snow weight is determined by subtracting the weight of the empty tube and caps from the total weight of the capped snow tube. Snow density is calculated as follows:

$$\rho = \frac{W_{total} - W_{tare}}{d_s * pi * r^2}$$

where W_{total} is the total weight of the tube, snow and caps in kg; W_{tare} is the weight of the tube and caps in kg; d_s is the snow depth in m; and r is the radius of the snow tube in m, measured as the inner diameter of the tube divided by two.

Observers also record the time of albedo observations, cloud cover, snowfall since previous observation, and note whether melt occurred since the last observation. Cloud cover is classified

into one of four categories: (1) all clear (0% cloud cover), clear (1% to 30% cloud cover), partly cloudy (30% to 60% cloud cover), and overcast (> 60% cloud cover). The lead author participated as a CoCoRaHS observer at the Thompson Farm Research Station in Durham, NH (NH-ST-99), collecting snow depth, snow density, and albedo data in the same manner as the CoCoRaHS volunteer observers described above over a mowed pasture.

Calibration of Apogee MP-200 Pyranometer

A study comparing the K&Z CMA6 albedometer and the Apogee MP-200 pyranometers was performed to calibrate the upwelling (SW_{up}) and downwelling (SW_{down}) radiation measured by the MP-200 units distributed to the volunteer observers. A Kipp and Zonen CMA6 albedometer and two Apogee MP-200 pyranometers, one facing upward and one facing downward, were mounted and leveled on a horizontal boom positioned 1.5 m above a mowed pasture pointing south at Thompson Farm Research Station in Durham NH (Figure 1; NH-ST-99). The CMA6 collected upwelling and downwelling radiation in the spectral range 285-2800 nm, sampling data every 10 seconds and recording the 30-minute average over the period 16-Dec-2011 and 15-Mar-2012. The MP-200 pyranometers sampled every 30 seconds and recorded the 30-minute average in their built-in dataloggers. Daily average albedo for the MP-200 was collected between 4-Jan-2012 and 15-Feb-2012, resulting in 43 days of albedo observations that overlap with the Kipp and Zonen CMA6 over the mowed pasture. The albedometers were serviced daily to check for leveling, download recorded data from the dataloggers, and cleaned if necessary.

Any snow that accumulated on the upward facing units was removed as soon as possible after snowfall concluded. Values impacted by snowfall or frost accumulation identified by visual inspection of the upper dome of the CMA6 and the upward facing Apogee MP-200 were removed from the analysis. For both the CMA6 and MP-200s, daily average daytime albedo is calculated as the sum of the 30-minute averaged upwelling (SW_{up}) radiation values greater than 1 W/m^2 divided by the sum of all corresponding downwelling radiation (SW_{down}),

$$\alpha_s = \frac{\sum SW_{up}}{\sum SW_{down}}$$

The low-cost Apogee MP-200 pyranometers compare very well to the K&Z CMA 6. SW_{down} values are strongly correlated ($r^2=0.9918$) and have a weak negative bias of -1.036 W/m^2 (Figure 2a). SW_{up} radiation is also strongly correlated ($r^2=0.9916$) with a positive bias of 4.797 W/m^2 (Figure 2b).
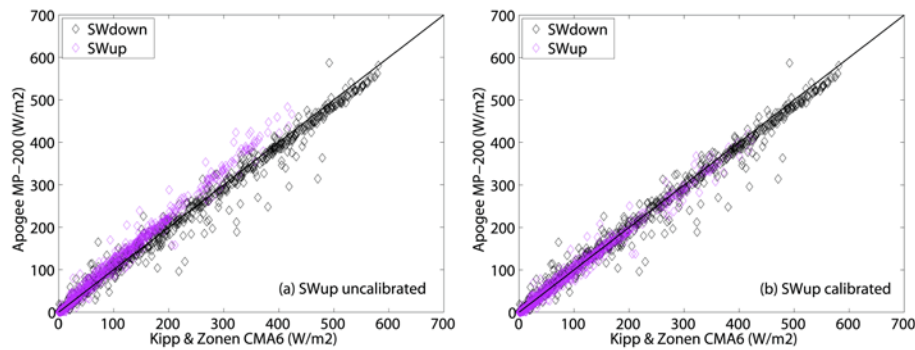

Figure 2. Scatterplots of Apogee MP-200 pyranometers versus Kipp and Zonen CMA6 albedometer for upwelling (pink) and downwelling (black), shown for (a) uncalibrated MP-200 data and (b) calibrated data collected over the period 4-Jan-2012 and 15-Feb-2012. Black line shows the 1:1 relationship.

Combined, the negative bias in SW_{down} and positive bias in SW_{up} result in a net positive bias of 0.05 in MP-200 albedo that remains fairly stable through solar zenith angles up to 70° (Figure 3), within the absolute accuracy range of 0.02–0.05 required for climate models to simulate the

surface energy budget (Henderson-Sellers, 1983). The maximum solar zenith angle of albedo data collected by CoCoRAHS observers was 67.8° at NH-CS-10 on 22-Dec-2011. The CoCoRAHS volunteer network albedo data set is therefore considered suitable for land surface and climate model albedo parameterization and/or validation.
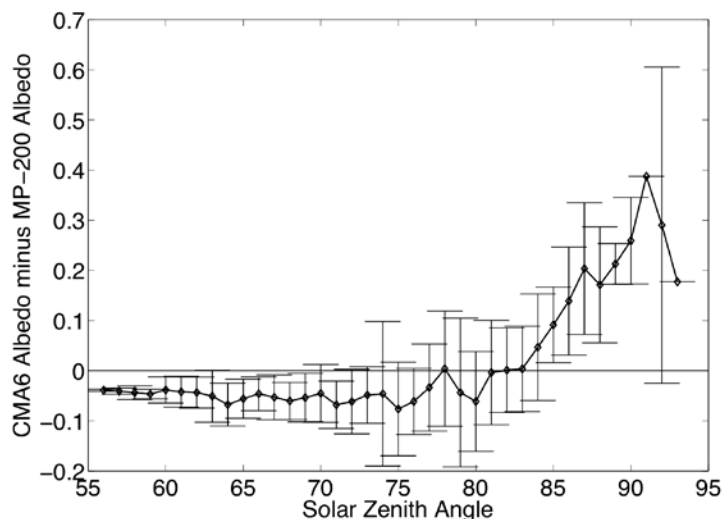

Figure 3. Difference in albedo measured by Kipp and Zonen CMA6 albedometer and Apogee MP-200 pyranometer mounted on leveling boom versus solar zenith angle, collected between 4-Jan-2012 and 15-Feb-2012 over mowed pasture in Durham, NH.

When the slope of pairwise linear regression between the K&Z CMA6 and MP-200 is used to calibrate the MP-200 upwelling radiation values (Figure 4a), the positive bias in albedo is reduced to 0.01 (Figure 4b), well within the range of an absolute accuracy of 0.02–0.05 required by climate models to simulate the surface energy budget (Henderson-Sellers and Wilson, 1983). The calibration study was carried out using two of the twenty MP-200 units; the remaining nineteen MP-200 units distributed to observers will undergo calibration for SW_{up} in Fall 2012. CoCoRaHS albedo values reported in the results section below are therefore considered to have a positive bias of 0.05.
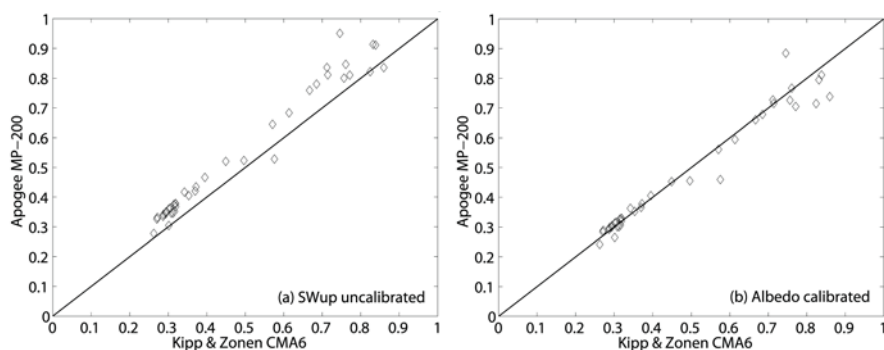

Figure 4. Scatterplots of MP-200 versus CMA6 daily average albedo for (a) uncalibrated and (b) calibrated data collected over the period 4-Jan-2012 and 15-Feb-2012. Black line shows the 1:1 relationship.

Analytical Spectral Devices FieldSpec4 Spectral Albedo

Spectral albedo measurements were collected using an Analytical Spectral Devices FieldSpec4 (FS4) Standard-Resolution Spectroradiometer in the range of 350–2500 nm using the ASD Remote Cosine Receptor (RCR) foreoptic at six sites within the CoCoRaHS Network (Table 2).

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The RCR passes light through a diffusing disc with a 180° field of view into a fiber optic cable composed of 57 fibers, nineteen fibers leading to each of the three detectors. The visible/near infrared detector (VIS/NIR) has a spectral resolution of 3 nm and sampling interval of 1.4 nm between 350–1000 nm. The two shortwave infrared (SWIR1 and SWIR2) detectors each sample at 10 nm resolution with a 2 nm sampling interval between 1000–1800 nm and 1800–2500 nm, respectively. The RCR foreoptic was mounted to the end of a 91.4 cm rectangular aluminum boom and leveled at a height of 80 cm above the snow surface using a bubble level located at the observer's end of the boom, collecting sky raw digital number (DN) when pointed upward and reflected raw DN when pointing downward.

Table 2. Site characteristics for ASD FieldSpec4 spectral albedo measurements.

Station ID	Surface Type	Date	SZA[a]	LSN[b]	Snow Depth (cm)	Days since last snowfall	Snow Density (kg/m^{-3})	Cloud cover (%) and Type
NH-CH-04	grass lawn	14-Mar-2012	45.1°	11:58:19	0	--	--	10%, scattered cumulus
NH-CR-01	snow w/ debris	28-Feb-2012	51.1°	12:01:28	12.7	4	276	0%
NH-CS-10	snow	29-Feb-2012	52.0°	11:57:29	30.5	1	403	100%, altostratus
NH-RC-13	snow	6-Mar-2012	48.3°	11:54:25	17.8	5	226.8	0%
NH-RC-29	grass lawn	12-Mar-2012	45.9°	11:54:20	0	--	--	5%, cirrus
NH-ST-99	snow	4-Mar-2012	49.2°	11:55:22	20.3	3	189	100%, stratus

[a] Solar Zenith Angle
[b] Local Solar Noon reported in EST (UTC −5)

Spectral albedo was obtained by dividing reflected raw DN by incoming raw DN from ten consecutive upward and downward measurements collected at each site around local solar noon, which was determined using the NOAA Solar Noon Calculator. Solar zenith angle at local solar noon ranged from 45.1° at NH-CH-04 to 52.0° at NH-CS-10. Snow-free measurements were made over grass lawn at three CoCoRaHS sites and snow-covered measurements were made at two CoCoRaHS sites and the mowed pasture at Thompson Farm (Table 2). Snow conditions over grass lawn sites included 30.5 cm one-day old snowpack, 17.8 cm five-day old snowpack and 12.7 cm four-day old snow with leaf litter and debris. The snow covered pasture measurements were made over a 20.3 cm three day old snowpack. Measurements were made under either clear-sky conditions or uniformly overcast conditions to reduce the effects of passing clouds.

RESULTS

The winter snow season of 2011/2012 was one of the warmest and least snowy on record according to the Northeast Regional Climate Center (www.nrcc.cornell.edu), who compile and summarize climate data for the northeastern United States. New Hampshire average monthly temperatures ranged from +2.4°C (+4.3°F) above average in November 2011 to +4.7°C (+8.5°F) above average in March 2012. Total monthly precipitation was below normal for every month except December, which was 107% of normal with respect to the 1980–2010 climatology. February precipitation had the smallest fraction of expected snowfall, receiving 34% of normal precipitation.

The maximum snow depth recorded by the CoCoRAHS observers was 50.8 cm (20.0 in.) at NH-CS-10; the remaining observers recorded maximum snow depths in the range of 16.5 cm (6.5 in.) to 34.3 cm (13.5 in.). Maximum snow depth at Thompson Farm was 26.7 cm (10.5 in.) at the mowed pasture.

CoCoRAHS

The Sixteen of the nineteen CoCoRaHS observers regularly reported data throughout the 2011–2012 snow season. The remaining three observers found that the noontime requirement could not be met or that their field sites did not provide adequate sunlight for measurements.

Daily average snow-free albedo over mowed grass ranged from 0.21 ± 0.06 to 0.33 ± 0.10 (Figure 5a). The bare soil at NH-MR-06 snow-free albedo was 0.21 ± 0.06, and the snow-free albedo of the wooden observation deck at NH-GR-11 was 0.30 ± 0.03. The pasture at Thompson Farm (NH-ST-99) average snow-free albedo was 0.33 ± 0.03 as measured by the MP-200 and 0.28 ± 0.04 as measured by the CMA6.
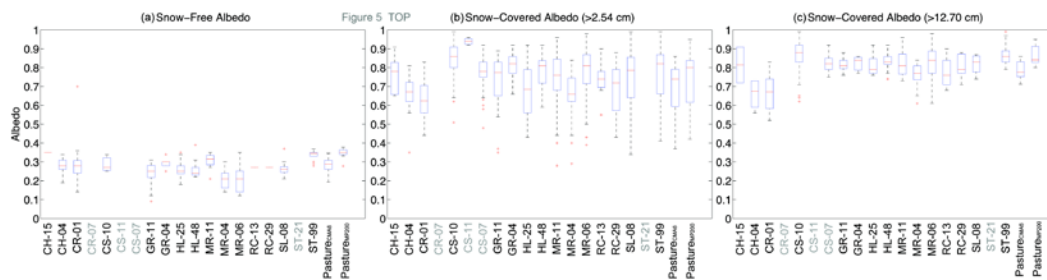

Figure 5. Box plots for CoCoRAHS albedo during (a) snow-free, (b) snow depth > 2.54 cm, and (c) snow depth > 12.70 cm conditions, showing median (red line), whiskers indicate upper 75th and lower 25th quartiles, and red crosses indicate outliers ($\pm 2\sigma$).

Mean albedo increases at all sites in the presence of snow cover (Figure 5b, 5c). Snow-covered albedo over mowed grass ranges from 0.61 ± 0.12 to 0.94 ± 0.02. Snow-covered soil at NH-MR-06 is 0.62 ± 0.17. Over the observation deck at NH-GR-11, snow albedo is 0.78 ± 0.10. The pasture at Thompson Farm (NH-ST-99) daily average MP-200 snow albedo is 0.67 ± 0.22 for the CMA6 and 0.69 ± 0.15 for the MP-200. Outliers falling below 2σ occur when snow pack is shallow and/or patchy and the range in albedo values is generally lower when snow pack is deeper (Figure 5c). The range in albedo values among CoCoRAHS stations is generally greater during periods of snow cover compared to snow-free conditions.

During periods of snow cover (i.e., snow depth is greater than 0 cm), surface albedo is positively correlated with snow depth at all CoCoRaHS stations (Table 3). The snow albedo versus snow depth correlation is statistically significant (p-value < 0.05) at thirteen of the fifteen CoCoRAHS stations. The three stations that found they did not have adequate sunlight or could not make the noon-time commitment did not have enough data to calculate correlation coefficients. Across the state of New Hampshire, CoCoRaHS snow albedo exhibits a logarithmic increase with snow depth (Figure 6a). The logarithmic equation illustrated in Figure 6a is the fit to all New Hampshire data. Individual station r-values are considerably higher and exhibit much less spread than the average statewide fit (Table 3). As an example, mean daily albedo is significantly correlated with snow depth at the pasture (r = 0.8193, p < 0.0001), and increases logarithmically with snow depth (Figure 6b).

Negative correlations are found between surface albedo and snow density at fifteen of the sixteen CoCoRAHS stations with adequate data; thirteen of the fifteen negative correlations were found to be statistically significant (p-value < 0.05). Three stations did not collect enough data to report snow albedo and density correlations. When analyzed for the entire state of New Hampshire, snow albedo exhibits a linear decrease with snow density (Figure 7a). Two stations, NH-GR-11 and NH-CH-04, report unrealistically high snow density values exceeding 600 kg m³ on numerous occasions, well outside the range of published values between 10 kg m⁻³ and 550 kg

m^{-3} (Hodgkins and Dudley, 2006; Baxter et al., 2005; Shulski and Seeley, 2004; Doesken and Judson, 2000). Albedo is significantly correlated with snow density at the mowed pasture (r = −0.5131, p=0.0103) and decreases linearly with snow density (Figure 7b).

Table 3. Correlation coefficients and significance (p-value < 0.05 highlighted in bold) for daily average albedo versus snow depth and versus snow density for CoCoRaHS stations in New Hampshire.

| Station ID	Lat	Lon	# obs	Snow Depth (>2.54 cm)		Snow Density	
				r	p	r	p
NH-CH-15	42.9395	−72.3284	11	0.2566	0.5050	**−0.9107**	**0.0017**
NH-CH-04	43.0676	−72.2187	21	0.4735	0.9674	−0.1559	0.7125
NH-CR-01	43.6037	−70.9867	58	**0.3000**	**0.0113**	**−0.3361**	**0.0121**
NH-CR-07	43.9295	−71.0841	0	--	--	——	--
NH-CS-10	44.4961	−71.5764	76	**0.4597**	**0.0048**	**−0.4507**	**0.0001**
NH-CS-11	44.3882	−71.2695	3	--	--	——	--
NH-CS-07	44.3764	−71.6132	86	**0.4172**	**0.0007**	**−0.3793**	**0.0009**
NH-GR-11	44.1467	−71.9650	43	**0.7117**	**0.0018**	**−0.6729**	**0.0000**
NH-GR-04	43.7603	−71.6889	18	0.6396	0.8044	−0.1951	0.5654
NH-HL-25	42.9141	−71.6102	22	**0.8285**	**0.0001**	**−0.4595**	**0.0478**
NH-HL-48	42.7767	−71.7799	24	**0.7637**	**0.0002**	**−0.5554**	**0.0059**
NH-MR-11	43.1499	−71.5565	39	**0.5061**	**0.0182**	**−0.6046**	**0.0002**
NH-MR-04	43.5200	−71.8190	80	**0.8448**	**0.0034**	**−0.4232**	**0.0004**
NH-MR-6	43.2849	−71.9253	74	**0.4496**	**0.0031**	**−0.3859**	**0.0015**
NH-RC-13	43.0159	−70.8272	9	**0.6437**	**0.0314**	0.3675	0.3705
NH-RC-29	42.9007	−71.1926	21	**0.6781**	**0.0312**	**−0.6320**	**0.0275**
NH-SL-08	43.4201	−72.0910	53	**0.6248**	**0.0042**	**−0.6111**	**0.0000**
NH-ST-21	43.2356	−71.0823	0	--	--	——	--
NH-ST-99	43.1087	−70.9487	34	**0.8193**	**0.0002**	**−0.4831**	**0.0168**
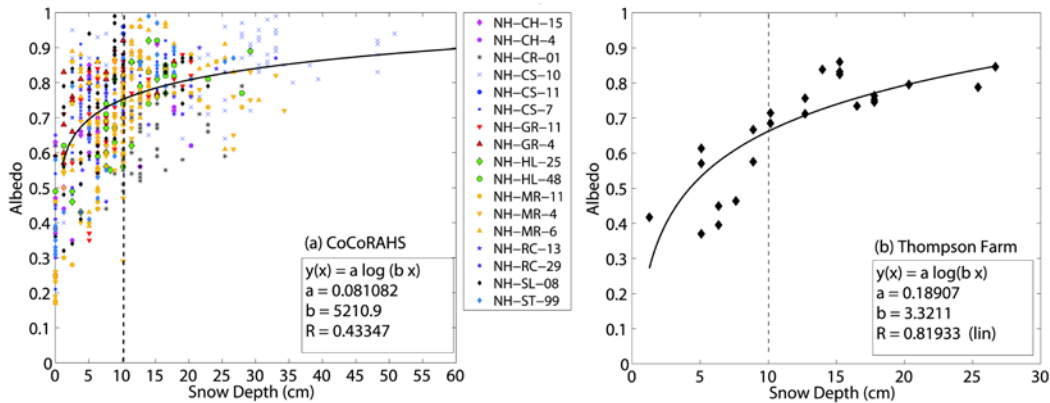
Figure 6. (a) CoCoRaHS albedo versus snow depth and (b) Thompson Farm CMA6 albedo versus snow depth. Dashed vertical line at 10 cm indicates the 5% (1%) visible (infrared) light transmission level from Perovich et al. (2007).
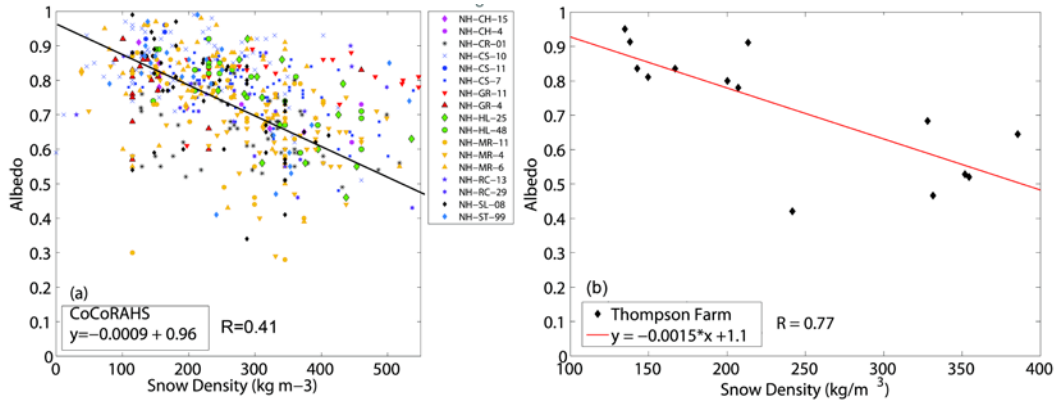
Figure 7. (a) CoCoRaHS albedo versus snow density and (b) CMA6 albedo versus snow density at the Thompson Farm Research Station.

Spectral Albedo

Spectral albedo in the visible (VIS) part of the spectrum (380–750 nm) is low for snow-free conditions and high for snow-covered surfaces. The VIS albedo measured over dead or senescent grass ranges from 0.02 (380 nm) to 0.33 (750 nm) at NH-CH-04 and from 0.03 (380 nm) to 0.35 (750 nm) at NH-RC-29 (Figure 8a). Albedo increases sharply between 680 nm and 780 nm at the transition zone between VIS and NIR. NIR gradually increases from 780 nm to 1000 nm, reaching a maximum 0.50 (1120 nm) at NH-RC-29 and 0.48 (1110 nm). Strong water vapor absorption around 1400 nm, 1900 nm, and beyond 2200 nm account for the noisy signal at these wavelengths. Snow-covered VIS albedo for fresh, deep (30.5 cm) snow ranges from a minimum of 0.90 (381–383 nm) to a maximum of 0.93 (741–743 nm) to at NH-CS-10 (Figure 8b). The shallower (20.3 cm), three-day old snow at Thompson Farm has a minimum VIS albedo of 0.89 (749 nm) and reaches a maximum of 0.92 between 541nm and 562 nm. The 17.8 cm, five-day old snowpack VIS albedo ranges from 0.83 (381 nm) to 0.87 (579 nm). The littered snow at NH-CR-01 has the lowest VIS albedo ranging from 0.71 (376 nm) to 0.73 (389-394 nm). Albedo declines rapidly from 780–1400 nm. NIR albedo is markedly higher for the fresh snowpack at NH-CS-10 compared to the three-, four-, and five-day old snowpacks at NH-ST-99, NH-CR-01, and NH-RC-13, respectively.
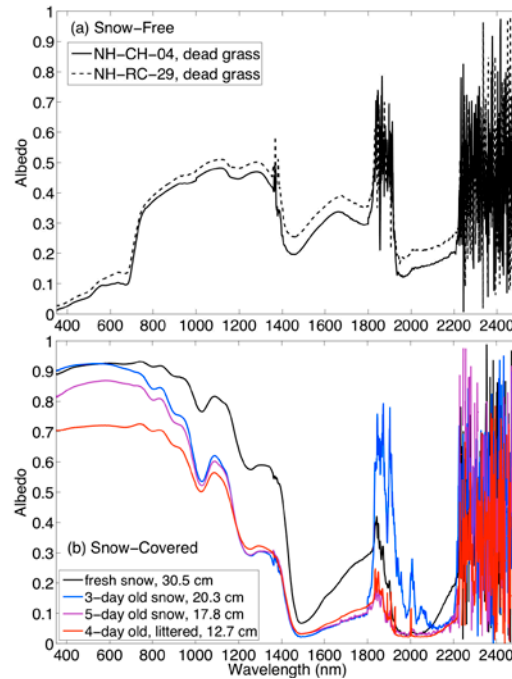
Figure 8. Spectral albedo of (a) snow-free dead grass and (b) snow-covered dead grass and pasture. Spectral curves represent the mean spectral albedo of ten albedo measurements.

DISCUSSION

The CoCoRAHS albedo pilot project shows great promise to provide high quality albedo data across the state of New Hampshire. Snow-covered (0.61–0.94) and snow-free albedo (0.21–0.35) values for deforested landscapes (i.e., dead grass and mowed pasture) agree well with previous mid-latitude studies. Albedo of dormant grasslands in Sasketchewan during the BOREAS study was about 0.20 for snow-free conditions, and 0.75 for snow-covered conditions (Betts and Ball, 1997). In Minnesota, the snow-free albedo of sod, alfalfa, and soybean fields ranges from 0.07 to 0.35 and snow-covered albedo ranges from 0.55 to 0.95 (Baker and Ruschy, 1989).

The logarithmic relationship between snow depth and albedo captures the change in reflectivity expected as a snow pack becomes optically thick and the influence of the underlying ground albedo becomes irrelevant. Baker et al. (1991) estimate critical snow depth to be about 10 cm for average values of snow density and grain size. At 10 cm, a snow pack reduces light transmission in the visible (500 nm) to 5% and to less than 1% in the infrared (Perovich, 2007). In this study, albedo begins to plateau around 10 cm according to the logarithmic fit in Figure 7.

The observed linear decrease in albedo with increasing snow density is likely related to increases in snow grain size as the snow pack ages, rather than a direct dependence on snow density. As grain size increases, the likelihood of a photon being absorbed while passing through a snow grain increases while the probability of being reflected by an air-ice interface decreases (Warren, 1982). Experiments by Bohren and Beschta (1979) reveal insignificant changes in snow albedo when snow density is artificially increased by compacting snow with a snowmobile, presumably maintaining constant grain size. Field notes recorded by the CoCoRAHS volunteers with phrases such as "corn snow," "grainy," and "granular" associate higher snow density (> 30%) measurements with larger grain sizes, but observers were not instructed to note changes in grain size routinely. In addition, the decrease in NIR albedo with the older, "grainy" snowpacks is consistent with modeled decreases in NIR albedo with increasing grain size (Painter et al., 2009; Warren, 1982). Future field seasons with CoCoRAHS volunteers will include measurements of

grain size in field observations to establish whether a proxy relationship between snow density and grain size exists in New Hampshire snow measurements.

CONCLUSION

Despite record breaking warm temperatures and below average snowfall, the first pilot season of albedo data collection with the CoCoRaHS Network in New Hampshire successfully identified interesting relationships amongst albedo, snow depth, snow density, and land cover using a low-cost tool kit. Albedo increases logarithmically with snow depth and decreases linearly with snow density over non-forested landscapes. Grain size measurements in subsequent field seasons may link snow pack metamorphism to changes in snow density. Albedo increases dramatically over in the presence of snow cover in non-forested surfaces, consistent with previous studies. The relationships amongst albedo, snow, and land cover will help improve models to accurately simulate wintertime climate and hydrological responses to changes in the surface energy budget. The CoCoRAHS Albedo Network will be combined with a network of tower, aircraft, and satellite albedo measurements to investigate the climate response to historical and future land cover change in the heavily reforested Northeastern United States. In the coming years, we hope to expand the volunteer albedo network to more snowy states across the US. The CoCoRaHS Network has already established itself as the largest provider of daily precipitation data in the United States. The volunteers in the New Hampshire pilot project who collected daily snow property data in the 2011–2012 winter season have put the capital "A" for Albedo in CoCoRAHS.

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