A Cost-Effective Automated Sensor Network for Meteorological and Snow Depth Measurements

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ABSTRACT

Cost and time requirements for consistently measuring meteorological forcing and snow depth in areas with heterogeneous physiography often limit the potential for snow model and remote sensing validation. This paper reports on the development and testing of an automatic sensor network (ASN) that measures soil and snowpack temperature profiles, snow depth, air temperature, humidity, reflected light intensity, and wind speed. The anemometer, consisting of half ping-pong balls attached to four arms extending orthogonally from the shaft of a low-resistance electric motor, was calibrated in a wind tunnel. Recent deployments of the ASN at mixed deciduous, mature Hemlock and open sites within the Harvard Forest of northern Massachusetts suggest low maintenance requirements under a broad range of meteorological conditions. Each ASN consists of three HOBO® loggers with internal and external sensors and one outdoor surveillance camera that takes daily snapshots of an 8X8 meter graduated snow stake grid and stores them on a laptop computer. Bi-weekly site visits provided snow pit density profiles of a snowpack with approximately 0.5 m depth at maximum. Comparisons of hourly measurements at the three sites show important differences between soil-snow temperature profiles and other measured variables that will improve the forest-snow algorithms in snow models.

Keywords: automatic sensor network, cost-effective, snow depth, forest

INTRODUCTION

Forest cover modifies the meteorological forcing of snow cover beneath deciduous and coniferous canopies. Snow cover dramatically increases the reflectivity and insulation characteristics of the underlying surface, both of which tend to decouple the surface from energy transfer with overlying atmosphere. Numerous modeling studies have shown that climate projections are extremely sensitive to snow cover extent and depth (IPCC, 2007). Gelfan et al. (2004) provides a comprehensive report on recent advances in forest cover modeling in snowy regions. One such model, UEBMOD, developed by Hellström (2000a, 2000b) and recently modified as part of the Snow Model Intercomparison Project phase II (SnowMIP2: http://users.aber.ac.uk/rie/snowmip2.html) effort, will be used to simulate forest cover effects on the snow cover at a long-established ecological research site in New England, the Harvard Forest (HFR) in central Massachusetts. New Englanders often say “if you don’t like the weather in New England, just wait a few minutes,” and this is substantiated by the highly variable weather on multiple spatiotemporal scales in Massachusetts, particularly during the Fall, Winter and Spring season. Prognostic weather models of storm tracks, such as GFS and NAM, commonly are

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inconsistent and diverge over New England a day or two prior to storm arrival. This project establishes a cost-effective automatic observation network in region with highly variable winter-time precipitation. Measurements and visual observations from this sustained project will provide input and validation data for forthcoming snow modeling using UEBMOD.

Dramatic changes in forest coverage in New England over the past two centuries, largely attributed to human causes, such as logging, agriculture, urbanization and infestations, are presumed partially responsible for locally rising temperature trends over the 20th century (Keim et al., 2003; Trombulak and Wolfson, 2004). Since 1970, this region has seen increases in temperature of 0.25°C/decade and changes in other related indicators consistent with a warming climate. Jones and Moberg (2003) suggest that the warming may be most pronounced during the winter months. In New England, decreasing trends in snowfall (Huntington et al., 2004) and six-fold increase loss of forest cover by anthropogenic development (Foster, et al., 2005) in the second half of the 20th century, together with this strong regional warming trend, will affect the magnitude, duration and timing of snow cover. Several hydrological indicators, such as earlier occurrences of ice melt on ponds and rivers (Hodgkins et al. 2000; Dudley and Hodgkins, 2002) and high river flow (Hodgkins et al. 2003) associated with early snowmelt, are consistent with surface warming trends. Yet studies that quantify the sensitivity of 20th century warming to forest cover change are lacking, particularly during the winter and spring when snow plays an important role in New England culture and climate.

Annual snow pack magnitude and dynamics influence the water retention and runoff characteristics of watersheds. Headwater streams and wetlands provide natural flood control, recharge groundwater, trap sediments, recycle nutrients, support biological diversity, and sustain the productivity of downstream rivers, lakes, and estuaries. Such streams also comprise at least 80% of the nation’s 17 stream network and offer the greatest opportunity for exchange between terrestrial and aquatic systems (Meyer et al. 2003). Despite providing essential ecosystem services that are increasingly threatened, headwater streams are relatively poorly studied and receive limited regulatory protection. In particular at HFR, intensive measurements of snow pack are lacking, which will contribute to a better understanding of wetland hydrology.

Hemlock forests, particularly in New England, USA, could functionally disappear in a few decades from the outbreak of Hemlock Woolly Adelgid (Adelges tsugae), a rapidly spreading Asian insect that kills hemlocks of all sizes within 4-15 years of infestation, and associated increases in hemlock harvesting. Although mortality is not strongly related to stand or site factors, the low damage in northern Massachusetts may be related to cold winter temperatures that reduce HWA populations (Paradis and Elkinton 2005).

This project utilized cost-effective microloggers to measure in situ meteorological and snow variables necessary to validate energy and water budget sub-models integrated into the forest canopy component of UEBMOD. Accumulation stakes, web-cams and environmental sensors were installed at one open and two forest sites at HFR for the snow season November 2007 to mid-April 2008. This project will improve understanding of and reveal the most important processes controlling snow cover in forested regions of central Massachusetts.

MATERIALS AND METHODS

Study area

HFR is designated a long-term ecological 1200 ha research (LTER) site located in central Massachusetts, USA. The HFR LTER program examines ecological dynamics in the New England region resulting from natural disturbances, environmental change, and human impacts. The climate of HFR is cool, moist temperate with a July and January mean temperature ranging from 20°C to -7°C. Annual mean precipitation is 110 cm, and distributed fairly evenly throughout the year. Snowfall is highly variable from one year to the next and winter precipitation consistently includes a mix of rain, freezing rain, sleet and snow, as is common with cyclones tracking from the southwest and intensifying as they approach New England in the Fall, Winter, and Summer seasons. The physiography is classified as New England Upland Region, ranging in elevation from 220 to 410 m above sea level with moderately to well-drained sandy loam glacial till soils overlying granite, gneiss and schist bedrock. Vegetation consists of transition hardwood, white pine and hemlock regions.

This study establishes an intensive measurement network at an open site, and two eddy flux sites, the Little Prospect Hill (LPH) mixed hardwood and Hemlock Stand plots (Fig. 1). The eddy flux towers were established in 2000 at LPH and 2002 at the Hemlock Stand. The hardwood stand is primarily Red oak (*Quercus rubra*) and the conifer stand is primarily old growth Eastern hemlock (*Tsuga canadensis*). Fig. 2 illustrates the site characteristics of each site.

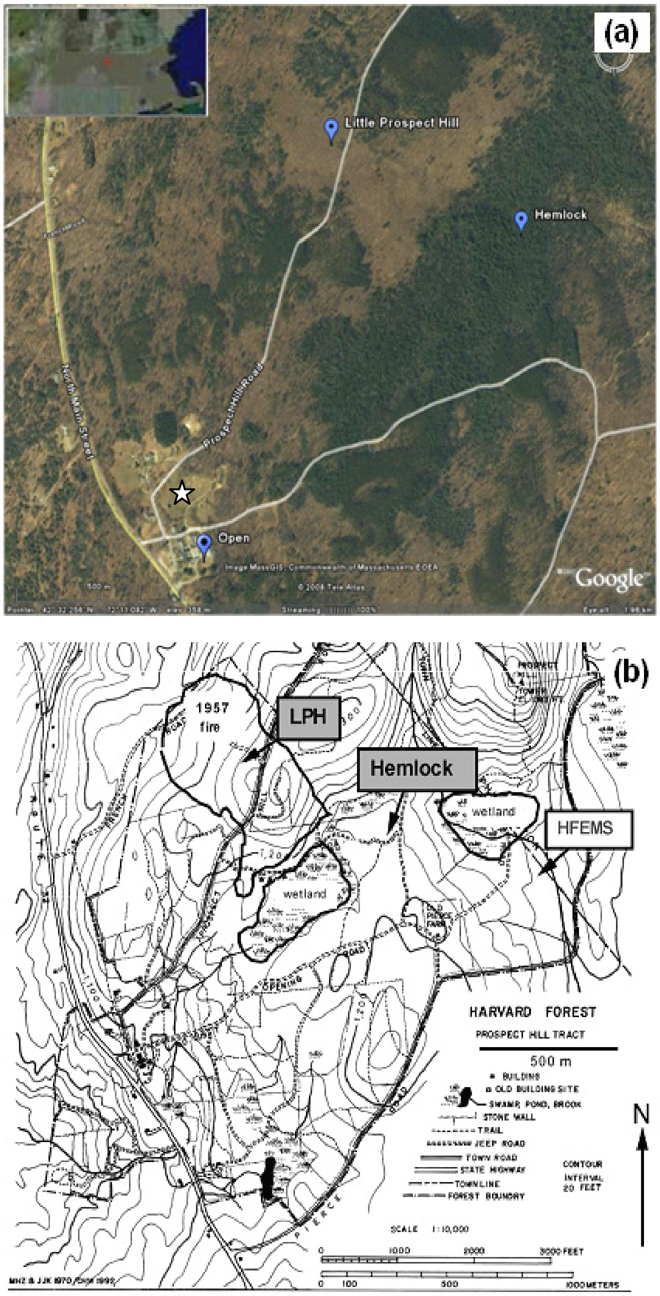

Figure 1. (a) Locations of test sites at Harvard Forest, 2007-2008. (b) Contour map showing terrain of the sites. Note the star in (a) denotes the location of a Campbell Scientific 10 m met. tower.

Table 1. Site characteristics: surface and tree stand height and effective leaf area index.

Site	*Slope (%)*	*Aspect*	*Elevation (m)*	*Height (m)*	LAI_e
Open	0	n/a	330	n/a	n/a
Hardwood	10	NW	380	16-20	1.82
Hemlock	0 *(hummocky)*	n/a	360	22	3.80

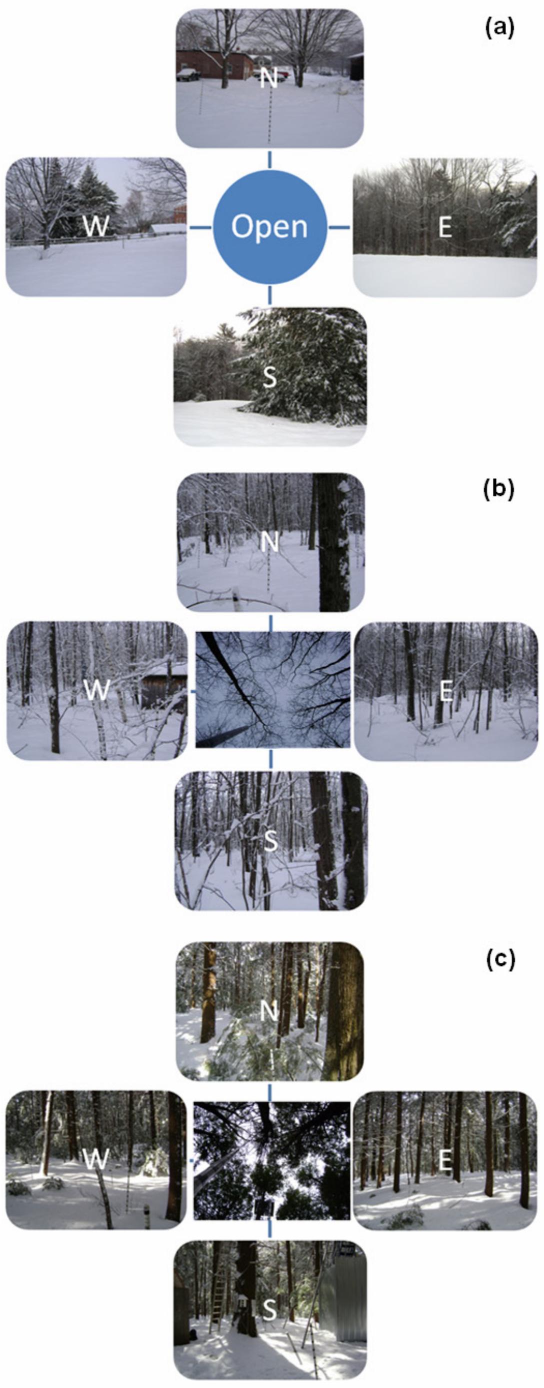

Figure 2. Photographs illustrating cardinal points of compass and upward from AWS sites: (a) open, (b) Little Prospect Hill, and (c) Hemlock sites (Fig. 1).

Instrumentation

Each automatic sensor network (ASN) consists of a nine 1.5 m graduated snow stakes equally spaced on a square 8x8 m grid and one AWS unit consisting of three HOBO® H12 battery powered loggers and one outdoor surveillance web cam aimed at the central stake.

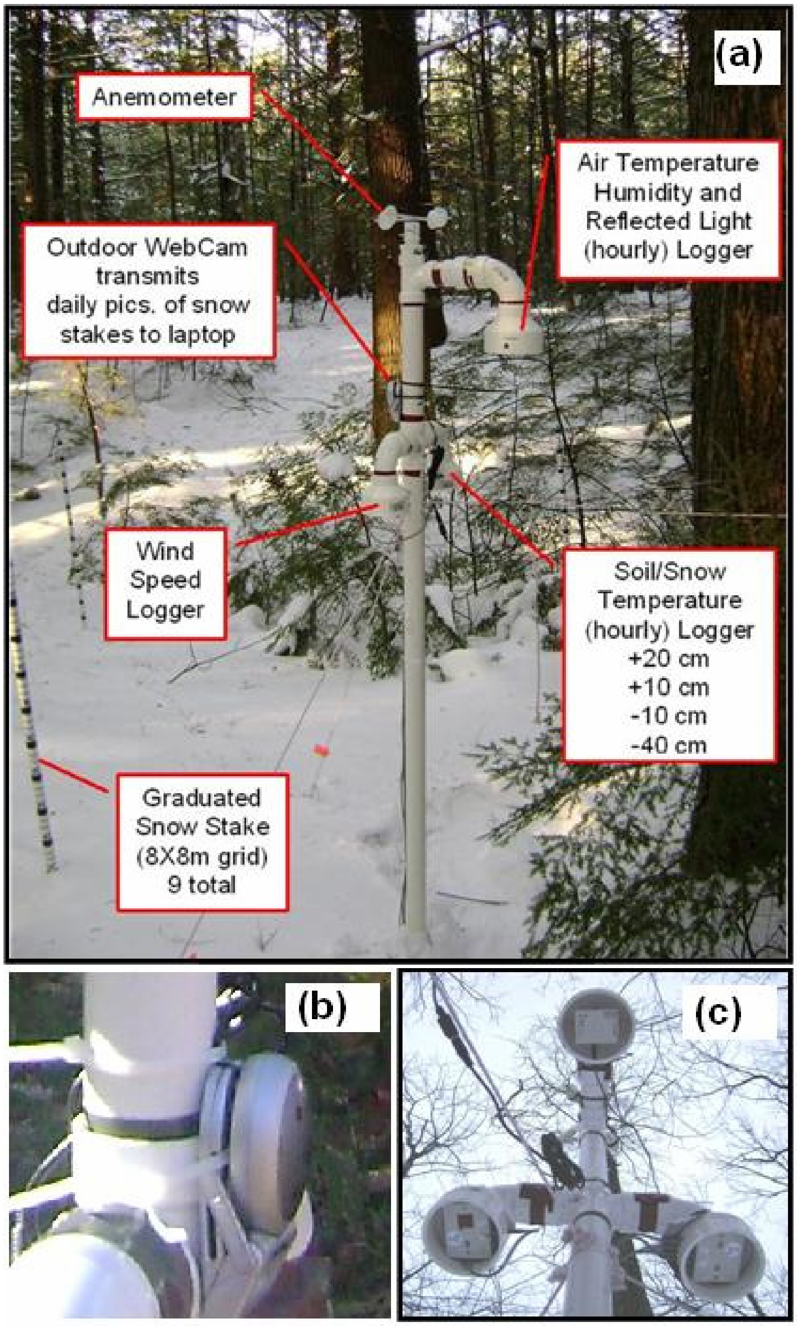

Figure 3. (a) AWS unit with sensors. Each site is set up identically. Temperature, humidity and wind speed were measured approximately 2 m above the ground. Note the snow stakes are graduated with 2 cm intervals up to 150 cm. (b) Lorex MCam transmits daily images of snow stakes to a laptop computer in a shed about 20 m from the AWS. (c) View from the bottom of the three PVC HOBO H12 logger enclosures.

Two major priorities of the ASN and HFR were keeping total cost below $2000. USD and maintaining accuracy and consistency between sensors at all sites. Table 2 summarizes the components and cost per site. Onset Computer (www.onsetcomp.com) has developed 12 bit resolution loggers that are easily embedded in small enclosures and have low power consumption. Because of the high cost for wind instruments (relative to budget constraints), they were fabricated around a small, low friction, DC motor using half Ping Pong balls glued to 3 mm thick by 10 mm wide clear plexiglass cross arms to produce a 200 mm diameter 4-cup anemometer. Anemometers were constructed and calibrated in a wind tunnel by undergraduate student assistants (Fig. 4).

Table 2. Components for a complete ASN at each site.

Item	*# /site*	*Cost/site (US $)*
LOREX outdoor MCam	1	$130
HOBO U12 Ta,RH, Light,Ext. Logger	1	$120
HOBO U12 4X Ext. Voltage/Current Logger	2	$190
Ground Temp. Sensors	4	$150
Anemometer	1	$10
PVC Stakes & Accessories	various	$30
Total Cost per Site	1	$630

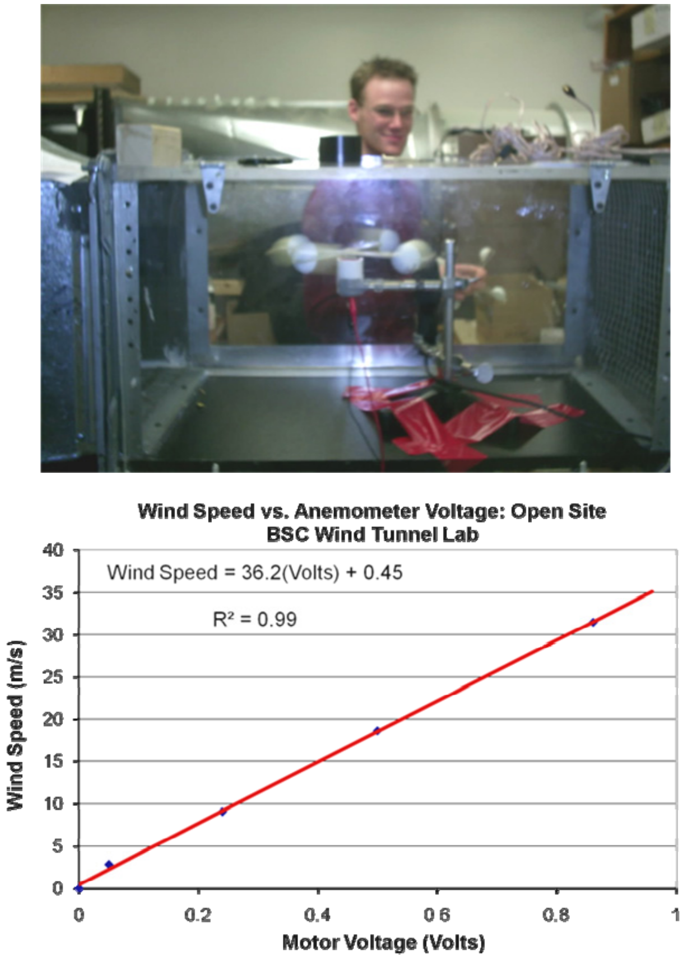

Figure 4. The four-cup anemometer was calibrated in the wind tunnel at Bridgewater State College.

Snow water equivalent (SWE) was calculated at each site through visual analysis of snow stake photographs (Fig. 5) and bi-weekly measurements of snow density profiles (Fig. 6).

Figure 5. Snow stake photo taken daily by the Lorex Mcam: hardwood site shown here. Each of 15 thick black markers on the stake is made of 2 cm thick Duck Tape and marks every 10 cm interval for a total of 1.5 m. Snow depth was found by counting markers down from the top and estimating snow surface to the nearest 2 cm .

Figure 6. Snow density profiles were taken with a 65 mm diameter by 60 mm deep anodized aluminum cylinder with serrated surface to help cut through ice layers. Each 100 cm^2 sample was placed in a Ziploc bag and massed to the nearest 0.1 grams. Densities ranged from 150 kg m^{-3} for newly fallen snow at the top of the pits to 800 kg m^{-3} at the base of pits at the end of the season.

Data analysis techniques

For the snowpack period, 10 December 2007 to 10 April 2008, temporal and regression plots were created from hourly averages of five-minute wind speed samples and hourly samples of substrate temperature, air temperature, and relative humidity. Plots of bi-weekly SWE at the two forest sites and the open site provided a base for comparisons of meteorological forcing at each site. Regression plots between each of the forest sites and the open site helped quantify differences in meteorological forcing including: air temperature, relative humidity, wind speed, and reflected solar. Because the air temperature logger is naturally aspirated it was compared to the temperature recorded for the same period by a standard 2-m, naturally aspirated, shielded sensor from the Campbell Scientific 10 m AWS, located in a large open pasture about 300 m north of the open site (Fig. 7); other meteorological variables were also compared (not show here). The -0.4 C offset is likely due to some solar heating error of the PVC enclosure for the HOBO H12 loggers. Note that the standard met. station temperature was less than the open site for the extreme high and low temperature end of the regression. Total insolation from the Campbell Met. tower is shown in Fig. 8 for the entire snowpack season, suggesting a strong upward trend throughout the season.

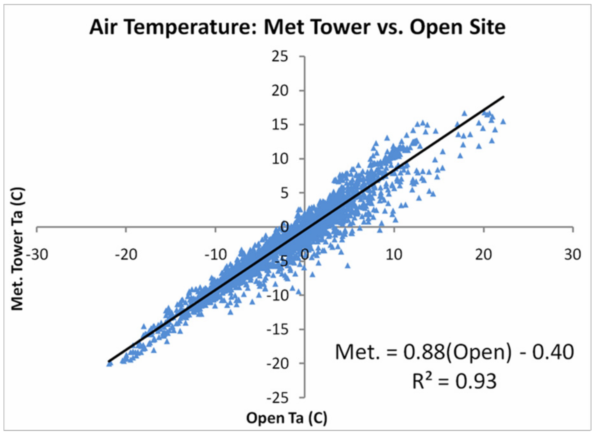

Figure 7. Regression of Campbell Scientific naturally aspirated, 2-m, air temperature vs. naturally aspirated open site HOBO H12 air temperature logger. Data are hourly from the entire snowpack season, 2007-2008. Note the regression equation.

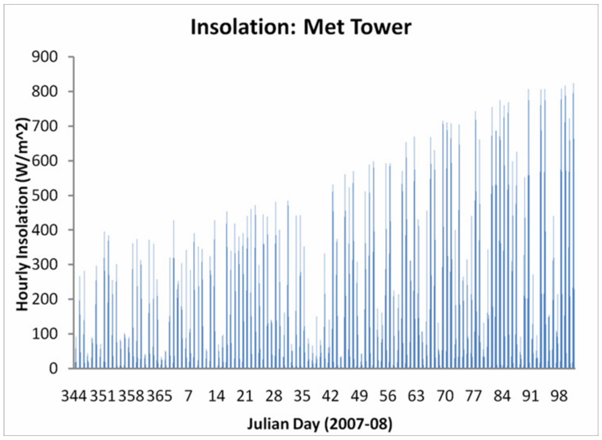

Figure 8. Insolation from atop 10-m Campbell Met. tower shown for snowpack period, 2007-2008.

RESULTS AND DISCUSSION

Comparisons of SWE (Fig. 9) indicate approximately 25% greater SWE at both forest sites when compared to the open site. Visual site inspections at bi-weekly visits confirmed significant interception and bridging between branches at both forest sites, with significantly greater amounts in the Hemlock canopy. Unlike many boreal sites (Pomeroy et al, 1998; Hedstrom and Pomeroy, 1998), the intercepted snow slipped out of the canopies within a day or two in agreement with other midlatitude sites (Hellström, 2000). The similarity in measured SWE confirms minor loss of intercepted snow due to sublimation. Snow density was consistently greater at the Hemlock site (data not shown), both do to compaction by slipping snow and greater infrared radiation by the greater diameter stems and over twice as great LAI_e (increased emitting surface area). Hence, snow interception processes and canopy stem size and density, along with air temperature, are important when modeling snowpack dynamics beneath conifer canopies. Peak accumulation, as shown between JD 56 and 63 (Fig 9), are almost identical for the two forest sites despite significantly different canopy characteristics. Post-peak SWE was slightly less for the hardwood than the Hemlock site, plausibly due to much lower insolation, as indicated by the decreased reflected light (Fig. 10d). Snowpack melt-out dates were earliest at the open site, lagged 3 days at the hardwood site, and lagged 5 days at the Hemlock site, largely due to the impacts of LAI_e on decreasing insolation and wind speed (Fig. 10c,d).

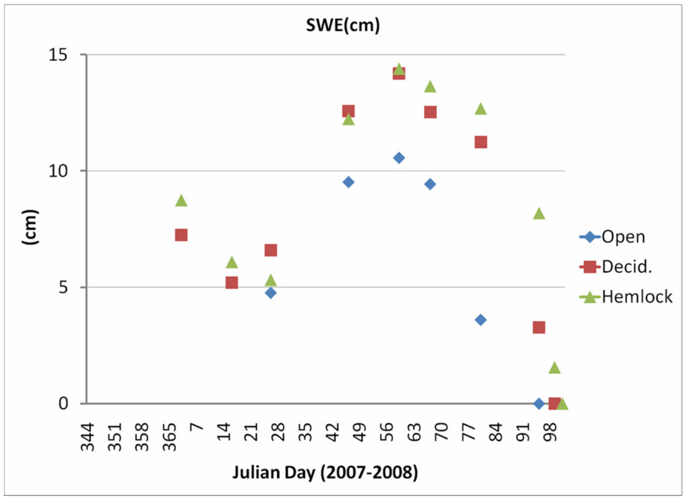

Figure 9. Snow density and depth were combined to get snow depth SWE at each of the sites.

When compared to the open site, air temperature (Fig. 10a) was cooler by 1.5 °C at the Hemlock and 0.5 °C at the hardwood sites, suggesting the dominance of decreased solar attenuation (Fig. 10 d) rather than canopy absorption and emission in controlling sub-canopy air temperature. The slope of the regression line suggests significantly higher Hemlock air temperature for open air temperature below -5 C and lower air temperature for open temperature above -5 °C. Some of the lower Hemlock temperature is due to radiation error at the open site, but as Fig. 7 suggests, this error is likely significantly lower that the observed differences of as much as 10 °C cooler than the open site. While the hardwood site has a similar tendency, the slope is 0.90, much closer to 1.0, than the 0.72 slope of the Hemlock regression. This temperature tendency for the Hemlock site is significant and warrants further scrutiny, future concurrent comparisons with aspirated sensors, and additional years of observation to include more types of winter weather. Relative humidity (Fig. 10b), largely due to it’s air temperature dependence, follows a similar pattern, but with significantly higher scatter for both forest sites. The fact that the offset is +35% for the Hemlock site and +15% for the hardwood site supports higher moisture content of sub-canopy air, particularly for the Hemlock site.

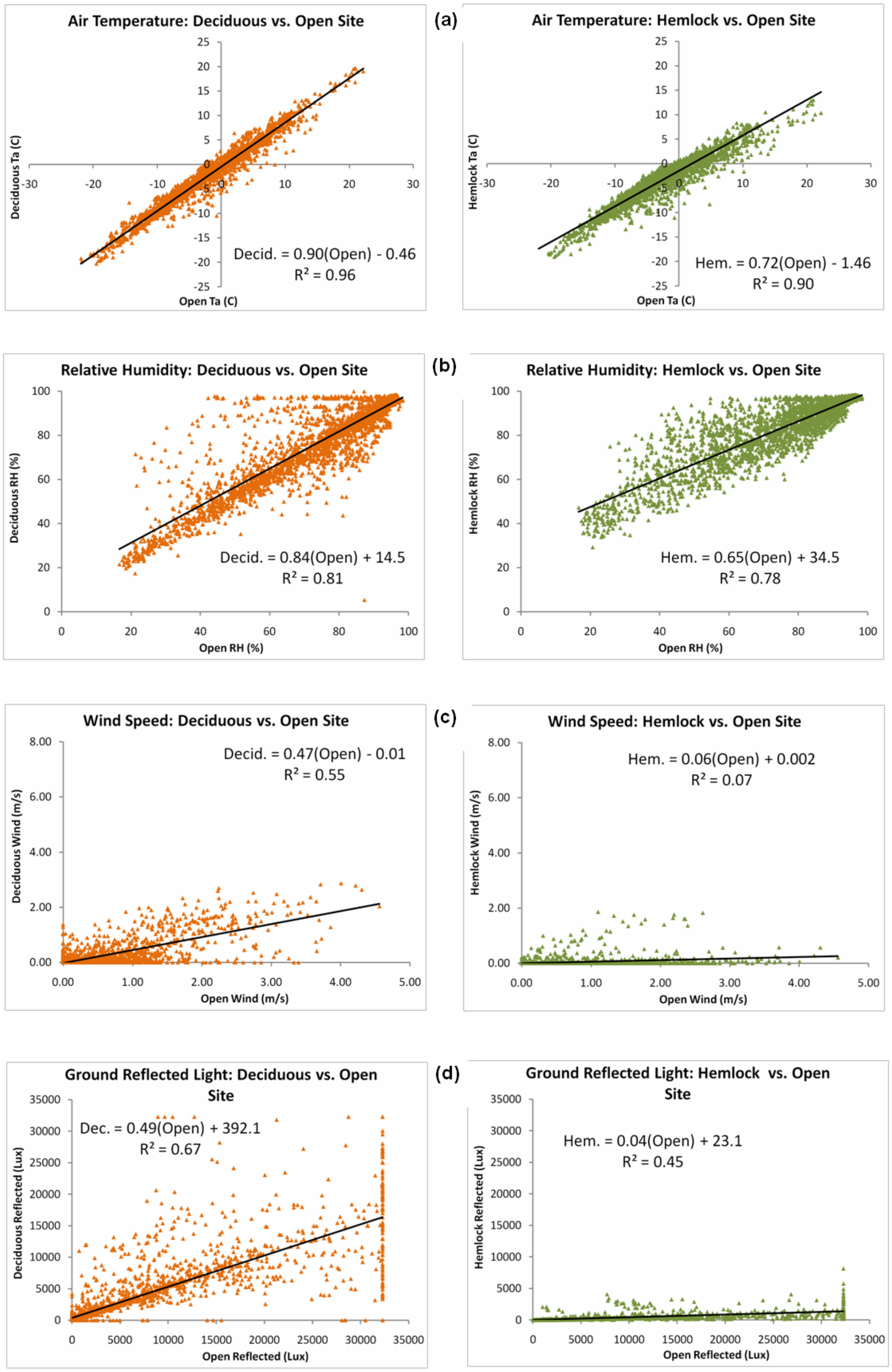

Figure 10. Linear regressions of forest sites vs. open site meteorological forcing: (a) air temperature, (b) relative humidity, (c) wind speed, and (d) reflected light intensity from surface (note the values of 32500 lux is the light sensor saturation value).

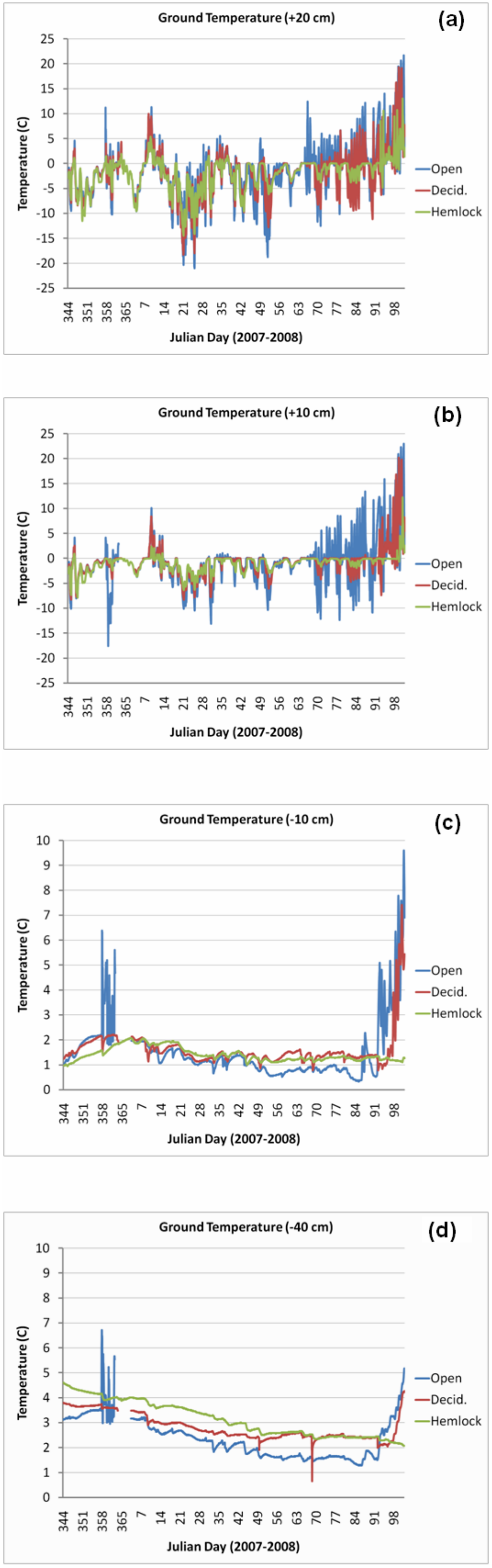

Figure 11. Thermistor measurements of: snowpack (or air) temperature at (a) +20 cm and (b) +10 cm from ground surface and substrate temperature at (c) -10 cm and (d) -40 cm from ground surface.

The adjacency of a swamp area may partially increase the sub-canopy moisture content at the Hemlock site. Sub-canopy wind speed (Fig. 10c) measured at 2 m above the ground at all three locations, was reduced by about 50% at the hardwood and 90% at the Hemlock sites, although the coefficient of determination was very low in both case, so it would be difficult to accurately represent sub-canopy wind with a simple linear regression of open site measurements, especially at the Hemlock site. The high variability of wind is largely due to turbulent eddies transferring momentum from the boundary layer down through the complex architecture of a forest canopy. Nevertheless, knowing sub-canopy wind speed and turbulence characteristics is critical for estimating sensible and latent sources of heat exchange with the snow surface. Fig. 10d shows results from a very cheap light-sensitive sensor embedded in the down-facing HOBO H12 logger, but it does demonstrate the relative difference in visible light (sensitivity between 0.6 and 0.9 μm) reflected upward from the snow or ground surface below. Reflected light from the hardwood site is about 50% and from the Hemlock site is about 10% that of the open site, demonstrating the non-linear relation between solar attenuation and LAI_e. Along with the windSnowpack and soil substrate temperature are shown in Fig. 11 to better understand the temperature gradients and hence direction of heat flux as snow accumulates and melts. Ground heat flux is upward throughout the snow season at all sites, decreasing from the first snowfall until melt-out. The snowpack temperature (Fig. 11b) rarely rises above freezing for the Hemlock and hardwood sites, although some slightly above freezing snow temperatures at the open site are common. The combination of higher wind speed to encourage wind pumping and greater insolation that penetrates to the thermistor are a plausible causes for this snowpack temperature difference at the open site. There is likely some minor radiation error associated with the +10 and +20 cm snow temperature probes as solar radiation attenuates through the overlying snowpack, especially for lower snow depths, and if the probe is exposed to the free air. This radiation error is minimized at the Hemlock site, so snowpack temperature is more reliable under canopies with higher LAI_e. Future experiments should attempt to set up an shading device to keep direct insolation from reaching the thermistor, or perhaps using a probe with a smaller sensor head. Figs. 11 a through d generally show higher diurnal and weather-related sensitivity from the highest to deepest probes. Some of the higher temperature after day 70 at the open site are likely due to increasing insolation (Fig. 9) and hence error, as the season advances, although some is likely warm air penetrating the snowpack with high wind speeds (Fig. 10c). Figure 11c shows that soil temperature at -10 C follows similar trend and variability for the three sites, ranging from +2.0 C to as low as +0.5 C at the open site, while the forest sites ranged from +2.0 C to +1.0 C with the least variability at the Hemlock site. Consequently, the substrate never freezes, at least not at -10 cm depth. Finally, the soil substrate temperature at -40 cm (Fig. 11d) began at +4.5 °C at the Hemlock, +4.0 °C at the hardwood, and +3.0 °C at the open sites and decreased, about two week prior to melt-out, to a low of +2.5 °C at both forest sites and +1.3 °C at the open site. The insulating properties of increased SWE in the snowpack (Fig. 9) between JDs 49 and 91 are evident, as shown by a relatively flat substrate temperature trend at all three site. The abrupt drop by 2 °C on JD 69 at the hardwood site is likely to the abrupt warming (Fig. 11a) and cold meltwater infiltration from the overlying snowpack. Several more moderate coldwater events occurred earlier between JDs 30 and 50 concurrently with slightly above freezing upper snowpack and air temperatures. The substrate quickly returns to the previous day's temperature, so this type of meltwater event has little impact on heat flux, but could significantly reduce the SWE of the snowpack.

CONCLUSION

A cost-effective ASN was set up at HRF for the 2007-2008 snow season using a combination of loggers and sensors from Onset Computer Corporation, outdoor surveillance web-cams, reused laptop computers, and fabricated anemometers. Undergraduate students assisted with fabrication and calibration of the anemometers using the wind tunnel facility at Bridgewater State College. Comparisons hourly measurements from the snow season provided valuable information about sub-canopy energetics at typical hardwood and Eastern Hemlock sites for Harvard Forest, a midlatitude, low altitude site influenced by coastal cyclones during the winter. Comparisons of SWE indicate approximately 25% greater SWE at both forest sites when compared to the open site with nearly identical peak SWE occurring at both sites after the last major snowstorm. Compared to the open site, which melted first, melt-out was delayed by 3 days at the hardwood and 5 days at the Hemlock sites. Results show lower air temperatures and higher humidities at forested when compared to open sites, particularly for the Hemlock site. Air temperature was, on average, about 1.5 °C colder at the Hemlock and 0.5 °C colder at the hardwood sites, although perhaps 0.5 °C of this cooler air temperature could be attributed to radiative heating of the enclosure, particularly at the open site. However, air temperature at the Hemlock site was higher than that of the open site for open site values less than -5 °C and lower than the open site for values greater than -5 °C. This trend toward warmer temperatures below the Hemlock during colder conditions will not lead to significant impact on the snowpack, but the lower temperature for above-freezing open values is plausibly responsible for the delayed melt-out at the Hemlock site. Relative humidity was consistently Wind speed was reduced to 10% at the Hemlock and 50% at the hardwood site as compared to the open site, 100%. Similar to wind speed, reflected light from the snow below the canopies were reduced to 10% at the Hemlock and 50% at the hardwood sites. Wind speed is critical when modeling sub-canopy sensible and latent heat flux, a significant component of meteorological forcing, especially during the melt period. Accurate modeling of attenuated insolation is an important component of sub-canopy energetic, particularly during the melt period. Substrate soil temperatures suggest a continuous upward heat flux at all three sites with highest values at the Hemlock site throughout the season. The initial -40 cm soil temperature was +5.0 °C at the Hemlock and +4.0 °C at the hardwood sites, and both trends converged at +2.5 °C after reaching the peak SWE of the snow season. By comparison, the -40 cm soil temperature at the open site fell from a peak of +3.5 °C to +1.5 °C at peak SWE. All three site maintained the low temperature until about two weeks prior to melt-out, largely due to air temperatures consistently 5 to 15 °C above freezing during the daylight hours. None of the sites experienced soil freezing at or below -10 cm depth, although snow pit density profiles excavated down to the substrate showed frequent freezing of the first cm of leaf litter and soil. Finally, and particularly at the hardwood site, several snow meltwater influx episodes were evident as moderate to day-long drops of 0.5 to 2 °C in substrate temperature at -40 cm. Solar insolation at all three sites is currently being measured by up-facing silicon pyranometers, but was not available for the 2007-2008 snow season.

The results of this study suggest that the Hemlock canopy suppresses extremes of temperature, generally keeping temperatures above -5 C below that of an open site. This may significantly deter the Wooly Adelgi infestation by keeping air temperature cooler for a longer period during the snow season, thereby prolonging the survival of the Eastern Hemlock. Furthermore, the measurements from the first year of this sustained ASN will help improve energy and water balance and canopy algorithms in the UEBMOD snow accumulation and ablation model. This field campaign will continue through future snow seasons to study annual variability and examine impacts of cyclone tracks. Future improvements will include replacing the HOBO H12 loggers with HOBO WiFi loggers which supports current efforts at HFR to set up a wireless network for real-time, remote control and access to data from LTER sites.

ACKNOWLEDGMENTS

Funding for this project was provided by Center for Advancement of Research and Teaching at Bridgewater State College. Thanks to Dr. Julian Hadley for access to and use of AC electric power at the Little Prospect Hill and Hemlock eddy flux research sites at Harvard Forest (Harvard Forest, Harvard University, 324 N. Main Street, Petersham, MA 01366, USA).

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