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Evergreen trees as inexpensive radiation shields for temperature sensors

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[1] Evergreen trees provide temperature sensors with shielding from solar radiation and an elevated location above the snowpack. Sensors were deployed with simple funnel radiation shields in the Sierra Nevada, California, and Rocky Mountains, Colorado. Compared with unaspirated, Gill-shielded thermistors, inexpensive self-recording temperature sensors hung in dense stands of trees have less than 0.8°C (0.4°C) mean difference in daily maximum (mean) temperature. In contrast, sensors in sparse and isolated trees had a bias of 2–5°C (0.3–1.3°C) in daily maximum (mean) temperature. Sensors on poles were biased 5–13°C (0.5–3.0°C) for daily maximum (mean) temperatures. In locations with deep winter snowpacks, sensors can be raised high into a tree using a pulley system.

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1. Introduction

[2] A realistic quantification of how temperatures vary over complex terrain is crucial to understand and model snowmelt [*Archer*, 2004; *Liston and Elder*, 2006; *Singh*, 1991], evapotranspriation [*Running et al.*, 1987], and ecological distributions [*Chen et al.*, 1999] across space and time. Low-cost, self-recording temperature sensors, such as Maxim iButtons [*Hubbart et al.*, 2005] and Onset Tidbits, Pendants, and HOBOs [*Whiteman et al.*, 2000], have been successfully used in many studies [*Lundquist et al.*, 2003; *Lundquist and Cayan*, 2007; *Mahrt*, 2006; *Marshall et al.*, 2007; *Pepin and Kidd*, 2006; *Tang and Fang*, 2006; *Whiteman et al.*, 2001], but accurately mapping temperature variations across a landscape continues to be a challenge [*Stahl et al.*, 2006, *Jarvis and Stuart*, 2001].

[3] One of the greatest challenges with successful deployment of inexpensive temperature sensors has been the development of an equally inexpensive radiation shield. The parameters most important for shield design include ventilation and shielding from both incident and reflected solar radiation [*Hubbard et al.*, 2001; *Tarara and Hoheisel*, 2007]. For snow hydrology applications, sensors must also be located high enough above the ground to avoid being buried by snow in the winter and to be above near-surface boundary layer temperature oscillations [*Nakamura and Mahrt*, 2005]. In wilderness settings, sensors should be hidden from view and not impact the environment. Evergreen trees, which cover most mountain areas in the western United States, meet all of these criteria.

2. Methods

[4] To test the comparability of temperature sensors deployed in trees to naturally aspirated Gill-shielded [*Gill*, 1979, 1983] and Stevenson screen–shielded [*MacHattie*, 1965; *World Meteorological Organization*, 1961] temperature sensors, we deployed iButtons in trees adjacent to clearings with routinely operated meteorological sensors at three locations along the eastern slope of the Rocky Mountains, Colorado, and at three locations along the western slope of the Sierra Nevada, California (Table 1). Sensors sampled hourly for the period from August 2005 to July 2006, spanning elevations from 1500 to over 3200 m and investigating tree types including Ponderosa Pine (*Pinus ponderosa*), Lodgepole Pine (*Pinus contorta*), White Fir (*Abies concolor*), and Subalpine Fir (*Abies lasiocarpa*). All sensors were deployed with an upside-down funnel shield developed by Jason Hubbart (personal communication, 2005), which shielded them from solar radiation from above but not reflected solar radiation from below (Figure 1). The funnel shield is less important than the tree in providing shielding from solar radiation (see section 3) but protects the sensors from rain and snow and helps researchers find the sensors again.

[5] All sensors were submerged in an ice bath prior to deployment and were accurate to within ±0.2°C. This matches the accuracy found by *Hubbart et al.* [2005] for iButtons (0.21°C) and by *Whiteman et al.* [2000] for Onset HOBOs (0.26°C). An iButton sensor deployed inside a Stevenson screen next to a mercury thermometer on Niwot Ridge, CO had a mean difference of −0.4/+0.4/−0.1 for maximum, minimum and mean daily temperatures, respectively (Table 1), all within the range of the manufacturer stated accuracy of ±0.5°C.

[6] To compare the effects of deployment within trees on measured temperature, iButtons were installed next to a California Department of Water Resources (CA DWR) meteorological and snow pillow station (in the Sierra Nevada) and next to two USGS meteorological stations

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Table 1. Tree Temperature Statistics Average Difference and Root-Mean-Square Difference Between Inexpensive Self-Recording Sensors and Reference Weather Station Measurements[a]

Site	Latitude (°N)	Longitude (°W)	Elevation (m)	Tree Type and Deployment Type	T_{mean} Bias/RMSD (°C)	T_{max} Bias/RMSD (°C)	T_{min} Bias/RMSD (°C)	T Hourly Bias/RMSD (°C)
Niwot C1 Stevenson Screen, Colorado	40.04	105.54	3000	in Stevenson screen	−0.09/0.35	−0.44/0.90	0.36/0.78	−0.10/0.90
Loch Vale Main Weather Station, Colorado	40.29	105.66	3200	dense trees (Subalpine Fir)	0.09/0.40	0.66/1.55	0.88/0.66	0.09/1.48
				pole	1.03/1.28	3.9/5.32	0.49/0.31	1.09/2.78
Andrew's Meadow Weather Station, Colorado	40.29	105.67	3200	dense trees (Subalpine Fir)	0.34/0.40	0.13/0.98	0.62/0.72	0.35/0.80
				single tree (Subalpine Fir)	0.91/1.06	2.43/3.58	0.79/1.05	0.91/1.94
				single tree (Subalpine Fir)	0.26/0.91	1.68/3.64	0.16/0.97	0.27/2.04
Hodgedon Meadow, California[b]	37.79	119.86	1500	dense trees (White Fir)	NA	NA	NA	NA
				pole	0.53/1.10	4.89/6.72	−2.03/2.49	0.67/4.14
				single tree (Ponderosa Pine)	0.08/0.73	2.71/4.02	−1.67/1.94	0.18/2.79
Porcupine Flat, California[b]	37.81	119.57	2500	dense trees (Lodgepole Pine)	NA	NA	NA	NA
				pole	1.00/1.27	4.24/5.87	−0.87/1.1	1.22/3.69
				single tree (Lodgepole)	0.78/0.99	1.64/3.36	−0.67/1.24	0.81/2.47
Tuolumne Meadows, California	37.87	119.35	2600	dense trees (Lodgepole Pine)	−0.05/0.68	−0.80/2.1	1.00/1.25	NA
				pole	3.14/3.50	12.63/13.63	−0.27/0.85	NA
				single tree (Lodgepole Pine)	1.13/1.27	4.83/5.26	0.06/0.69	NA
Average				dense trees	0.13/0.49	0.00/1.54	0.83/0.88	NA
				poles	2.09/2.39	8.27/9.48	0.11/0.58	NA
				single trees	0.77/1.08	2.98/4.16	0.34/0.90	NA

[a] Bias is the tree temperature statistics average difference; RMSD is root-mean-square difference. NA means not applicable.

[b] Reference measurements were not available at the two Sierra sites marked. At these sites, the pole and single-tree values were compared to the sensor in the dense stand of trees; these statistics were not considered in the average statistics.

(in the Rocky Mountains), where temperature is routinely recorded with a thermistor in a naturally ventilated Gill radiation shield on a pole 2.5 m above the ground. The CA DWR station used a Weathertronics 4350-A temperature-humidity probe, which has a stated accuracy of ±0.10°C. Incoming solar radiation was measured with a Licor LI-200SZ. Both sampled hourly. The Rocky Mountain stations both used Campbell Scientific Model 207 temperature and relative humidity probes, sampling every 15 min, with a manufacturer worst-case accuracy of ±0.4°C within the range measured. The 15-min samples were subsampled to hourly to compare with the iButton measurements. At each site, one iButton was mounted on the pole that held the reference temperature probe, one in a solitary pine, and one within a dense stand of pines.

[7] All of the sensors presented here were naturally aspirated by the wind, which can result in average temperature biases of 0.4–1.3°C [*Arck and Scherer*, 2001; *Georges and Kaser*, 2002] and biases in maximum temperature of up to 2°C on still days [*Hubbard et al.*, 2001]. *Hubbard et al.* [2001] found that natural ventilation was adequate to avoid bias in areas with persistent high winds (>3.5 m s^{-1}), which is the case for the two Rocky Mountain locations (average wind speeds were 7 m s^{-1} at the main weather station and 6 m s^{-1} at Andrew's Meadow). At Tuolumne Meadows in the Sierra Nevada, the temperature sensor in the dense stand of trees was on average cooler than the Gill-shielded sensor, likely because during times without strong winds the trees had less warming than the naturally ventilated Gill shield. (Although there were no wind measurements at the Tuolumne site, a nearby site had average wind speeds of 3 m s^{-1}.)

3. Results: Accuracy and Potential Bias of Tree-Deployed Sensors

[8] At each site, the temperature sensor in the dense stand of trees had the highest minimum temperature and the lowest maximum temperature, indicating that trees shield solar radiation during the day and emit additional longwave radiation at night (Table 1). Daytime differences were largest on sunny days, particularly when snow on the ground contributed to large amounts of reflected radiation. Figure 2 illustrates the temporal variation of temperature differences for Tuolumne Meadows, the site with greatest exposure to solar radiation. Where reference temperature data were available, temperatures measured by the sensor in the dense stand of trees most closely matched temperatures recorded by the reference sensor in the Gill radiation shield. Annual average differences were less than 1°C for both mean and minimum daily temperatures recorded by weather stations and sensors deployed in single or dense trees. Only sensors deployed in dense stands of trees had daily maximum temperatures with less than 1°C average annual difference. These results suggest that placing a sensor

Figure 1. An iButton in a funnel radiation shield in a tree.

within a dense stand of trees is more effective than placing a sensor within a funnel radiation shield.

[9] At Tuolumne Meadows, the difference between the temperature measured by the sensor on the pole, which lacked radiative shielding from below, and the temperature measured by the sensor within the dense stand of trees correlated well with independent measurements of solar radiation (R^2 = 0.78, Figure 3a). This correlation was significantly higher than the correlation of solar radiation with the diurnal temperature range, $T_{max} - T_{min}$ ($R^2 = 0.23$, Figure 3b), which is often used as a proxy for solar radiation when direct measurements are not available [*Bristow and Campbell*, 1984]. The temperature difference also closely tracked changes in surface albedo, with the daytime temperature difference nearly doubling when snow was on the ground (Figure 2c). Thus, pairs of differently shielded temperature sensors could provide a cheap proxy for distributed cloud cover (i.e., solar radiation) and albedo changes.

4. Deployment Techniques

[10] Where the maximum snow depth is shallow, sensors can be tied to a tree branch approximately 2 m above the ground. Where the maximum snow depth is deep, such as in the Pacific Northwest, sensors can be hoisted high in trees using a pulley system. At each site, we launch a weighted tennis ball attached to a nylon cord over a tree branch, tie the sensor onto a looped nylon cord, and raise the sensor high into the tree, attaching the bottom of the cord to the tree trunk or a lower branch. The resulting simple pulley system allows the sensor to be raised and lowered easily during subsequent downloads and replacements. Because all of the sensors described here must be manually downloaded to retrieve data, time in the following summer must be allocated to revisit all sites. Thus, these methods are generally more suitable for short-term campaigns than for long-term deployment.

5. Conclusions

[11] Evergreen trees provide shielding from solar radiation for temperature sensors, with average biases less than 0.4°C for T_{mean} and 0.8°C for T_{max}, as compared to

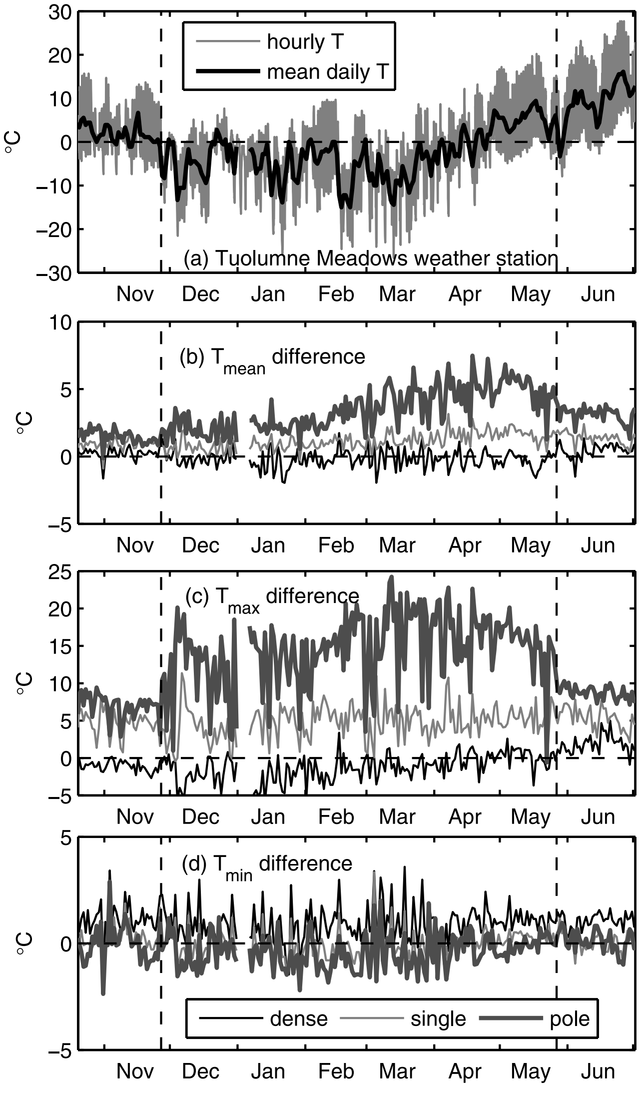

Figure 2. (a) Hourly and mean daily temperature recorded by the CA DWR Gill-shielded thermistor at the Tuolumne Meadows snow pillow site in Yosemite, California. Difference between (b) daily mean, (c) daily maximum, and (d) daily minimum temperatures recorded by iButton sensors mounted on a pole, within a single tree, and within a dense clump of trees, as compared to the official snow pillow sensor shown in Figure 2a. Horizontal dashed lines mark 0°C, or no difference. Vertical dashed lines mark the beginning and end of snow cover at the site. The legend in Figure 2d also applies to Figures 2b and 2c.

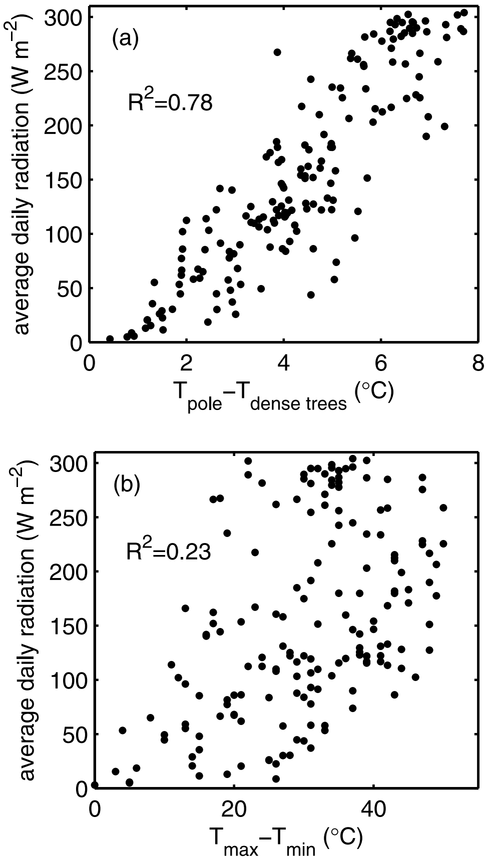

Figure 3. (a) Correlation of differences between mean daily temperatures (temperature of sensor hung on a pole minus temperature of sensor hung within a dense stand of trees) with daily average solar radiation. (b) Correlation of $T_{max} - T_{min}$ measured by the operational temperature sensor with average daily solar radiation for that same period.

naturally ventilated Gill-shielded thermistors. Thus, trees provide a cost-effective way to distribute inexpensive, self-recording temperature sensors. Sensors placed on poles above treeline are likely to be exposed to large amounts of solar radiation, with average warm biases of 2°C for T_{mean} and 8°C for T_{max}. The difference in temperature between a sensor placed in a tree and one placed on a pole is correlated with changes in solar radiation and thus provides proxy information about cloud cover.

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