VALIDATION OF AIRBORNE THERMAL INFRARED REMOTE SENSING OF SNOW SURFACE TEMPERATURE IN THE UPPER TUOLUMNE WATERSHED, YOSEMITE NATIONAL PARK, CALIFORNIA, USA

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ABSTRACT

Here we present 5-m spatial resolution thermal infrared measurements of snow surface temperature collected by a small airplane flying over the upper Tuolumne watershed in Yosemite National Park in February, 2016. The plane captured spatial and temporal variations in the temperature of the snow's surface, while concurrent ground measurements provided a reference point to evaluate the aerial measurements' accuracy. Thermal infrared measurements provide a diagnostic tool used to assess model representation of many key processes, including snowmelt rates, sensible and latent heat fluxes, and longwave radiation. Comparisons between airborne observations and ground based measurements indicate airborne observations reliably quantify snow surface temperature to within approximately 2°C. This difference indicates a considerable reduction in uncertainty when compared to modeled snow surface temperature. By correcting ground-based thermal infrared measurements for view angle snow surface emissivity effects, differences between ground based and airborne observations are reduced to approximately 1.5°C.
(KEYWORDS: surface temperature, remote sensing, ground validation, infrared)

INTRODUCTION

Modeling experiments have demonstrated snow surface temperature (T_s) and snow water equivalent (SWE) are significantly impacted by biases in forcing irradiances (Lapo et al., 2015). In order to reduce uncertainties associated with modeled representation of the snow energy balance, 5-m spatial resolution airborne thermal infrared (TIR) measurements of T_s were collected over the upper Tuolumne watershed in the early morning hours from 5-7 February, 2016.

Currently, satellite products, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, provide the only worldwide and temporally regular observations of land surface temperature across snow covered complex terrain. However low instrument resolution and temporal frequency, approximately 1km and four times daily respectively, introduce challenges with quantifying T_s in mountain environments. For example, material heterogeneity including trees and rocks are difficult to discern from snow under large observation pixels (Dozier and Painter, 2004). Furthermore, understanding the temporal evolution of T_s is complicated by infrequent observations. Together these factors motivate an observational framework with much finer pixel resolution such that we may a) quantify uncertainties in modeled and measured T_s and b) determine how T_s scales with decreasing spatial resolution of remote sensing instruments, so that we may collect a reliable signal from satellite observations.

EXPERIMENTAL DESIGN

To maintain visual contact between the ground and plane and to see maximum variability in T_s, airborne observations were acquired during a high pressure period over Yosemite National Park between 5 and 7 February, 2016. Three TIR cameras and one visual camera were mounted to the underbelly of a small airplane (Figures 1a and 1b). The plane completed an oval shaped flight path every ten minutes over the upper Tuolumne Basin just after sunrise each morning. Brightness temperature, the temperature measured by a TIR sensor, was assigned to each 5-m pixel throughout the study area for each flight overpass.

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TIR Cameras

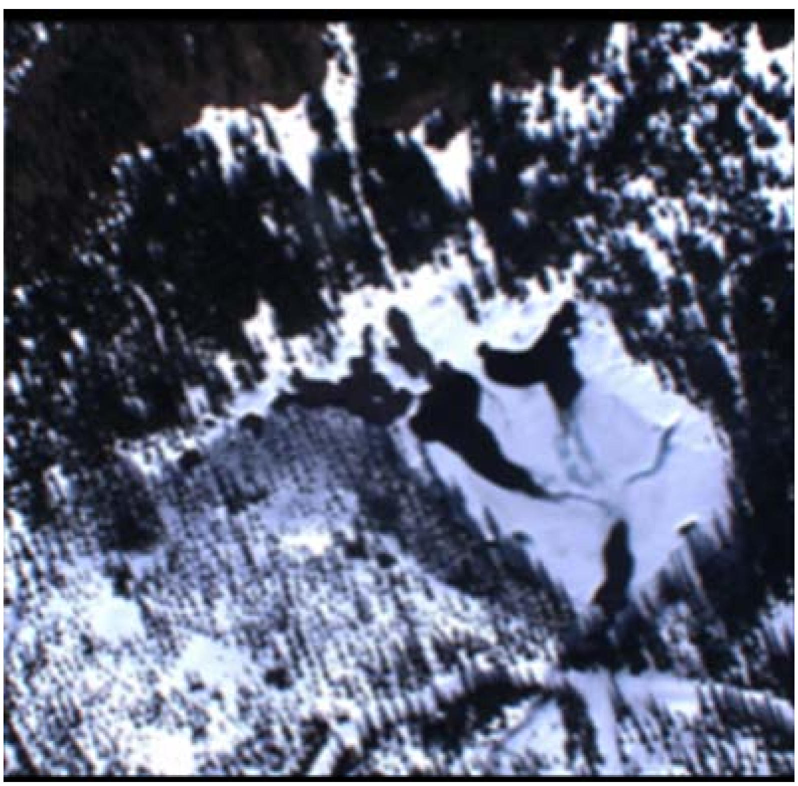

Figure 1a. Top: Small airplane with mounted TIR and visual cameras. Bottom: Visual image from 2013 test flight over Snoqualmie Pass, WA.

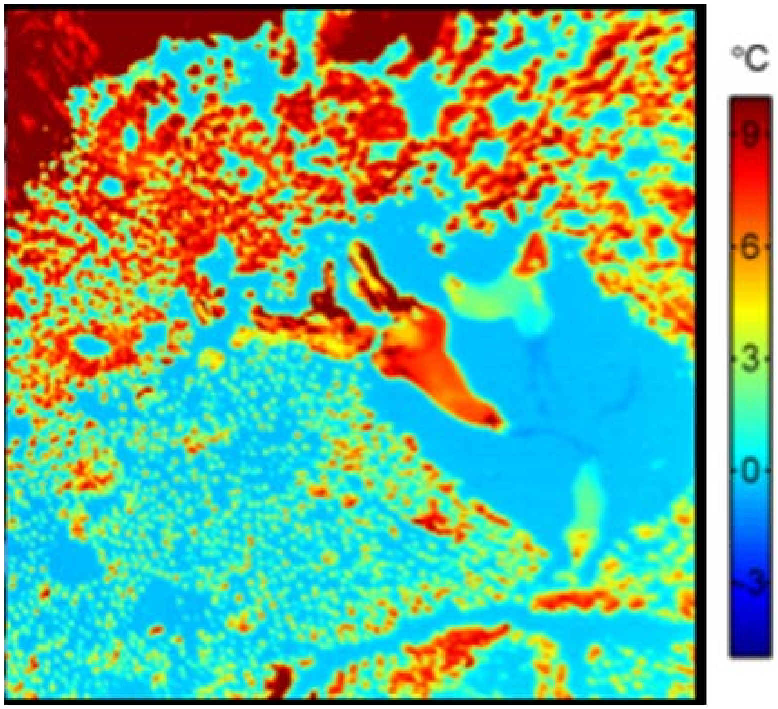

Figure 2b. Associated TIR image showing surface temperature variability of trees, rocks, and snow. Adapted from Lundquist et al., proposal. Sensing and Simulating Spatial Snow and Streamflow in the Sierra (S^6)

In order to quantify uncertainty in airborne TIR T_s measurements, a suite of ground based instruments are installed in order to simultaneously measure snow surface temperature at Dana Meadows, a large treeless meadow coincident with each flight overpass. Ground observations included an Apogee infrared radiometer, a TIR camera, a single pixel TIR thermometer, several dial-stem thermometers, HOBO temperature and relative humidity shuttles, and snow pack vertical temperature profile thermistors. Thus by comparing ground based observations to spatially and temporally corresponding airborne observations, the accuracy of airborne TIR measurements may be determined.

RESULTS

In order to establish a control in which the uncertainty of airborne T_s observations may be quantified, we choose ground based apogee infrared radiometer T_s observations to be our best approximation of the truth. Apogee observations have a low observational uncertainty and an observational footprint size similar to that of airborne observations. Airborne observations were consistently warmer than those of the Apogee; the largest difference between spatially and temporally coincident observations was 2.2°C, smallest 0°C, and mean 0.9°C (Figure 2). Comparisons between airborne observations and other ground based measurements indicate similar differences. Therefore it may be reasonably deduced that airborne observations characterize snow surface temperature in Dana Meadows to within approximately 2°C. This difference represents a considerable reduction in T_s uncertainty compared to model differences of approximately 10°C (Lapo et al., 2015).

Airborne observations were approximately nadir with respect to the snow surface in Dana Meadows, while the Apogee instrument was approximately 30° from nadir. As snow surface emissivity is a function of viewing angle, the emissivity of the snow surface was corrected to 0.99 for the Apogee instrument, while snow surface emissivity for airborne observations was left at 1.00 (Dozier and Warren. 1982). This correction raises Apogee T_s observations approximately 0.5°C such that the largest difference between spatially and temporally coincident observations was 1.6°C, smallest -0.5°C, and mean 0.4°C.

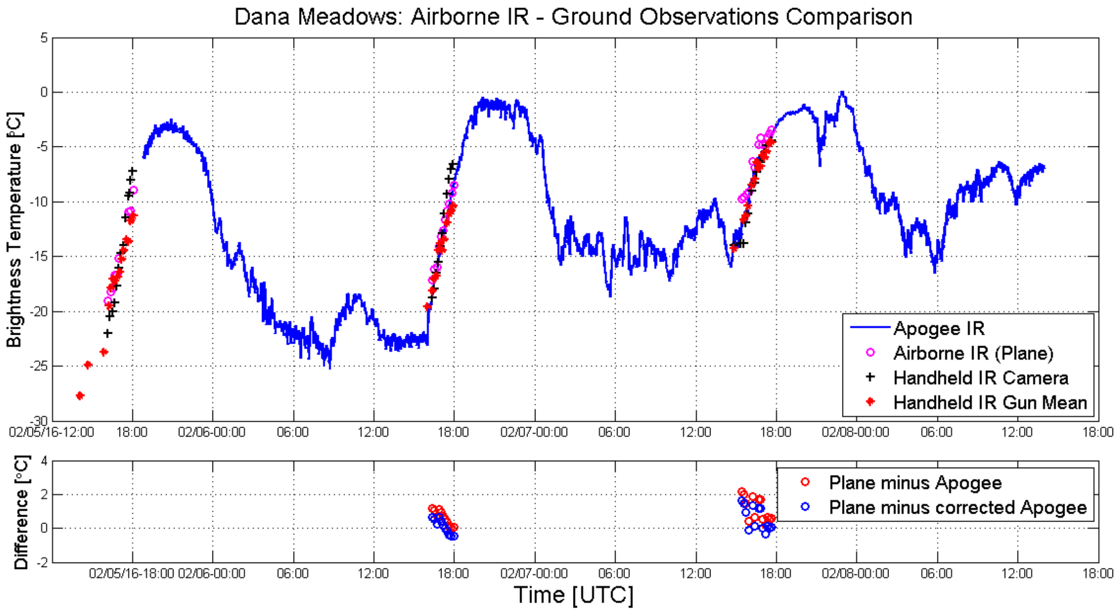

Figure 2. Top: Time series of snow surface temperature observations at Dana Meadows ground station. Apogee infrared radiometer observations (blue), airborne TIR observations (magenta circles), handheld TIR observations in (black crosses), and single pixel TIR thermometer (red circles). Bottom: Time series of airborne observations minus Apogee observations (red circles) and airborne observations minus surface emissivity corrected Apogee observations (blue circles).

CONCLUSIONS

We have introduced and validated a novel application of remote sensing, thermal infrared cameras mounted to a small airplane in order to collect high resolution spatially and temporally distributed snow surface temperature measurements in mountainous terrain. Ground validation comparisons indicate airborne observations reliably characterize T_s to within approximately 2°C. By applying a snow surface emissivity correction to non-nadir instruments the differences between airborne and ground based observations is reduced to within approximately 1.5°C. This analysis represents a considerable reduction in uncertainty when compared to modeled T_s. In addition, high resolution spatially and temporally distributed observations of T_s may be used to evaluate the energy balance of snow in complex terrain and assess model representation of many key processes.

LITERATURE CITED

Dozier, J., and T. H. Painter. 2004. Multispectral and hyperspectral remote sensing of alpine snow properties, *Annual Review of Earth and Planetary Sciences*, *32*, 465-494, doi: 10.1146/annurev.earth.32.101802.120404.

Dozier, J., and S. G. Warren. 1982. Effect of viewing angle on the infrared brightness temperature of snow, Water Resour. Res., 18(5), 1424–1434, doi:10.1029/WR018i005p01424.

Lapo, K. E., L. M. Hinkelman, M. S. Raleigh, and J. D. Lundquis. 2015. Impact of errors in the downwelling irradiances on simulations of snow water equivalent, snow surface temperature, and the snow energy balance, Water Resour. Res., 51, 1649–1670, doi:10.1002/ 2014WR016259.

Lundquist, J., Cristea, N., Hughes, M., Chickadel, C. 2016. Unpublished Proposal, Sensing and Simulating Spatial Snow and Streamflow in the Sierra (S^6).