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Near–surface air temperature and snow skin temperature comparison from CREST-SAFE station data with MODIS land surface temperature data

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Abstract

Land Surface Temperature (LST) is a key variable (commonly studied to understand the hydrological cycle) that helps drive the energy balance and water exchange between the Earth's surface and its atmosphere. One observable constituent of much importance in the land surface water balance model is snow. Snow cover plays a critical role in the regional to global scale hydrological cycle because rain-on-snow with warm air temperatures accelerates rapid snow-melt, which is responsible for the majority of the spring floods. Accurate information on near-surface air temperature (T-air) and snow skin temperature (T-skin) helps us comprehend the energy and water balances in the Earth's hydrological cycle. T-skin is critical in estimating latent and sensible heat fluxes over snow covered areas because incoming and outgoing radiation fluxes from the snow mass and the air temperature above make it different from the average snowpack temperature.

This study investigates the correlation between MODerate resolution Imaging Spectroradiometer (MODIS) LST data and observed T-air and T-skin data from NOAA-CREST-Snow Analysis and Field Experiment (CREST-SAFE) for the winters of 2013 and 2014. LST satellite validation is imperative because high-latitude regions are significantly affected by climate warming and there is a need to aid existing meteorological station networks with the spatially continuous measurements provided by satellites. Results indicate that near-surface air temperature correlates better than snow skin temperature with MODIS LST data. Additional findings show that there is a negative trend demonstrating that the air minus snow skin temperature difference is inversely proportional to cloud cover. To a lesser extent, it will be examined whether the surface properties at the site are representative for the LST properties within the instrument field of view.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

1 Introduction

As the direct driving force in the exchange of long-wave radiation and turbulent heat fluxes at the surface–atmosphere interface, LST is one of the most important parameters in the physical processes of surface energy and water balance at local through global scales. Knowledge of the LST provides information on the temporal and spatial variations of the surface equilibrium state and is of fundamental importance in many applications (Li et al., 2013). For this particular reason, LST is commonly studied to describe many topics, such as: evapotranspiration, climate change, the hydrological cycle, vegetation monitoring, urban climate and environmental investigations. However, given the complexity of surface temperature over land, oftentimes ground measurements cannot practically provide values over wide areas. Whereas, with the development of remote sensing from space, satellite data presents the possibility of measuring LST over the "entire" globe with sufficiently high spatial and temporal resolutions.

Over the last 15 years, remote sensing has come of age as a viable source of observations and monitoring, particularly in regions of the world where in situ networks are sparse. Many hydrological state variables and fluxes can be estimated through satellite remote sensing observations. Two observable constituents in the land surface water balance that are of importance are snow and ice. These cover vast (and often inaccessible) regions of the Earth that influence climate, culture, and commerce in significant ways (Tang et al., 2009). Unfortunately, in Arctic and sub-Arctic regions meteorological stations are scattered and poorly distributed geographically; these are mostly located along coastal areas and often unreachable by road (Hachem et al., 2012). The snow formed in these regions can cover up to 50 % of landmasses in the Northern Hemisphere (Dominé and Shepson, 2002). More importantly, snow cover plays a critical role in regional to global scale hydrological modeling because rain-on-snow with warm air temperatures accelerates rapid snow-melt, which is responsible for the majority of the spring floods (Chen et al., 2012). Therefore, high-latitude regions are significantly affected by climate warming and there is a need to aid existing meteorological station networks with the spatially continuous measurements that can be provided by satellites.

Although the needs for monitoring snow and ice temperatures are commonly known, the lack of ground measurements do not allow for the proper scrutiny. Because of this, research community are often obliged to take near surface air temperature, since it considerably resembles bare land surface temperature, as the LST even when that might not be the case under the presence of snow (Wan et al., 2004). Normally, LST satellite readings can be compared accurately to near surface air temperature because the algorithms have been developed this way (Vancutsem et al., 2010; Fu et al., 2011; Benali et al., 2012). Also, previous studies have compared the relationship between near surface minimum and maximum air temperature values and MODIS land surface temperature products (Zhu et al., 2013). Whilst a few others compare near–surface air temperatures and MODIS ice–surface temperatures (Shuman et al., 2013). This leads to the suspicion that maybe ground-measured LSTs in high-latitude regions covered in snow might not display congruent behavior with satellite readings. Because if the snow temperature satellite readings are far from the real values, this can lead to confusion when trying to predict the occurrence of avalanches or spring floods.

In this study, MODIS LST and observed T-air and T-skin data from the CREST-SAFE station for two winter sessions were investigated. Some possible reasons for discrepancy or agreement will be explained studying the daily time series for the two winters as well as the diurnal cycle for particular days.

2 MODIS instruments on TERRA and AQUA satellites

The MODIS instruments were launched on the Terra and Aqua platforms in December 1999 and May 2002, respectively (Crosson et al., 2012). Both the Terra and Aqua satellites have a sun-synchronous near-polar orbit. However, they ascend/descend the equator at different times. Terra descends (ascends) the equator around 10:30 a.m. (10:30 p.m.) LT. In contrast, Aqua descends (ascends) the equator at

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1:30 p.m. (1:30 a.m.) LT. MODIS has a viewing swath width of 2330 km, allowing global coverage every 1 to 2 days. The spatial resolution of the MODIS instrument varies with each spectral band and ranges from 250 m to 1 km at nadir (Hall et al., 2002).

The LST and Emissivity products used in this study were MOD11A1 (Terra) and MYD11A1 (Aqua). These products are tile-based and gridded in the sinusoidal projection with a 1 km resolution. The data are recorded twice (day-time and night-time views) daily and downloadable as HDF files. The HDF files have image dimensions of 1200 × 1200 for the whole globe. The LST day-time and night-time data for Caribou, Maine (46°52′59″ N, 68°01′07″ W) were extracted from these files. Afterwards, both the T-skin and T-air observed at CREST-SAFE were compared and linearly correlated to the MODIS LST data. In order for these comparisons to be fair, the specific times at which Terra and Aqua ascend/descend over Caribou were selected for the in situ observations. Terra MODIS records over Caribou commonly between 2 p.m. (2 a.m.) and 3 p.m. (3 a.m.) LT, while Aqua MODIS ascends/descends over Caribou sometime between 5 p.m. (5 a.m.) and 6 p.m. (6 a.m.) LT.

3 CREST-SAFE

The CREST-SAFE has been carried out since January 2011 (its setup was done during February 2010) at the research site (Fig. 1) of the National Weather Service office in Caribou, ME, USA (46°52′59″ N, 68°01′07″ W, 190 m elevation). In this long term experiment, dual-polarized microwave (originally 37 and 89 GHz; 10.65 and 19 GHz were installed afterwards) observations are accompanied by detailed synchronous meteorological observations. The objective of this field experiment is to improve the understanding of the effect of changing snow characteristics (i.e., grain size, density, temperature) under various meteorological conditions on snow microwave emission to improve snow cover properties' retrievals from satellite observations (Lakhankar et al., 2013).

Caribou has a humid continental climate and offers fitting conditions for snow studies. The cold season has an average daily high temperature below 0 °C and lasts from mid-December to early March. Snow cover commonly withstands from mid-November to early April. Regular seasonal snowfall is approximately 116 in (2.9 m). The record snowfall is 197.8 in (5.02 m) and it happened in the winter of 2007–2008.

An Apogee Infrared Radiometer is used to measure snow skin temperature directly by converting thermal energy radiated from the surface in its field-of-view (FOV) to an electrical signal with a response time of less than 1 s (Muñoz, 2014). This process is automated at every 3 min to an accuracy of 0.2 °C. The air temperature is measured directly by a Vaisala Temperature/RH Probe through an automated process; also at a 3 min sampling interval with the same accuracy.

4 Results and discussion

4.1 Time series analysis of snow skin and air temperature data

The snow skin and air temperature hourly data from the CREST-SAFE station were averaged daily for the two years (2013 and 2014) to understand the difference between them throughout the winter months with average daily cloudiness (Fig. 2). The average daily cloudiness was computed averaging the hourly cloud percentage for each day at Caribou, ME acquired from NWS website.

T-air (even in the coldest winter months) is higher than T-skin but shares the same trend. However, while the magnitude of the temperature difference (T-air – T-skin) is in the order of 1–3 °C between the months of December and February, it increases to 5–8 °C once March starts. While daily average temperature values might suggest this behavior, looking at the hourly values (Sect. 4.3) might indicate otherwise. Near-surface air temperature tends to affect the snow skin temperature directly, although the latter's fluctuations are not as drastic (Walsh et al., 1985). The record shows that the winter of 2013 was the coldest of the two (hourly lows of –26 and –36 °C in late January for T-air and T-skin, respectively). However, it cannot be ruled out that it is possible for the near surface air temperature to be colder than the snow skin temperature at particular times throughout some winter days, but not common on a daily average basis.

Figure 3 illustrates the relationship between cloud cover and the air minus snow skin temperature difference (T-air minus T-skin) and tries to cluster specific air temperature ranges to find certain patterns or behaviors. It demonstrates that whenever cloud cover is non-existent, so is its radiative cooling of the ground; resulting in lower T-skin and larger differences between the air minus snow skin temperatures. There is also a negative trend (as shown by the downward slope of the line) indicating that T-air minus T-skin will be inversely proportional to cloud cover. This temperature difference commonly ranges between 0–5 °C regardless of the average daily air temperature changes. When the average daily T-air is higher than 3 °C, the temperature difference can reach 10 °C. On those days when the average daily T-air is lower than −10 °C, the temperature difference ranges from 0–7 °C but never goes below zero. The T-air minus T-skin distribution is not clustered, which implies that it might not be solely affected by cloud cover. It is very likely that wind speed is affecting the temperature difference values as well.

4.2 Satellite and in situ correlation analysis

T-skin and T-air values (abscissas) vs. MODIS LST (ordinates) day-time and night-time data were plotted to obtain linear correlations (Figs. 4 and 5). In-situ observations were selected at the specific times both satellites ascend/descend over Caribou, ME.

R^2 linear correlations (Table 1) between the MODIS LST day-time data and in situ air temperature range from 0.83–0.87 to 0.80–0.85 for the Terra and Aqua satellites, respectively. However, for the snow skin temperature these correlations fluctuate between 0.45–0.78 (Terra) to 0.79–0.82 (Aqua). These values indicate that a higher correlation exists between T-air and the LST observed by the MODIS instruments. Satellite LST values do not correlate as well with the snow skin temperature values observed at CREST-SAFE. This is demonstrated by the low correlation value of 0.45 for Terra MODIS for the winter of 2014. LST night-time data correlations with T-air show even lower values ranging from 0.43–0.78 (Terra) and 0.65–0.86 (Aqua). T-skin correlations with the satellite data are also lower during night-time views (ranging from 0.30–0.71 for Terra and 0.59–0.82 for Aqua) as indicated in Table 2.

The incongruence between the day-time and night-time views is related to the radiative cooling of the land surface (and snow). If there is no (or weak) advection and no clouds, the T-air minus T-skin difference is mostly driven by the radiative cooling of the land surface because the radiative heating by the sun is quite small compared to it. However, the presence of clouds provides a substantial downward thermal flux which heats the surface and, to a lesser extent, the air; therefore reducing the T-air minus T-skin difference (Holtslag and De Bruin, 1988; Platt and Prata, 1993). This accounts for the lower night-time correlation values and the discrepancy between MODIS LST and T-skin. Section 4.3 explains how wind speed also affects this relationship.

Another remark is that the low correlation values between MODIS LST and in situ LST can be attributed to the fact that MODIS characterizes the brightness temperature of the vegetation (whose temperature should be closer to the air temperature) that is abundant in the vicinity of the field experiment (approximately 70 % grassland, 15 % residential homes, and 15 % paved roads). Satellite radiometry is applied to large areas (1 km in this study) which often consist of various land and vegetation types. When comparing satellite and in situ point-wise data the primary issue is whether the surface properties at the site are representative for land surface properties within the instrument field of view (FOV). The temperature of vegetation canopy is usually closer to the air temperature than to the land surface temperature, therefore for forested areas in winter the MODIS LST is better correlated with the air temperature (Yang et al., 2006; Dong and Peters-Lidard, 2010).

4.3 Diurnal cycle analysis

Eight days (two per month) from the winter (January–April) of 2013 were selected (Figs. 6a–d and 7a–d) to study the T-air minus T-skin difference throughout the diurnal cycle to further examine the large differences in the correlations between MODIS

LST and in situ temperature data. Also, wind speed and cloud coverage were taken into account to try to explain these disparities.

Figure 6 illustrates the coldest days of January (lowest temperature values recorded for the whole winter) and two days of mid-February. The record low for the winter (−36 °C) happened on 23 January under non-cloudy conditions and a low daily average wind speed of 5.15 ft s^{-1}. January and February temperatures peaked sometime between 12:00–2:00 p.m. LT and showcased the largest T-air minus T-skin differences from 2:00–6:00 a.m. LT and 3:00–7:00 p.m. LT. These are the specific times when Terra and Aqua ascend/descend over Caribou, ME. Given how it was previously established that MODIS LST better resembles near-surface air temperature, this helps explain the low correlation values between MODIS LST and T-skin. When looking at particular days, Fig. 6a shows that under low wind speed and non-cloudy conditions, the T-air minus T-skin difference is large. This leads to the understanding that the low MODIS LST and T-skin correlation values can be partially attributed not only to the clouds' downward thermal flux but to wind speed as well. Figure 6b demonstrates a day with high wind speed conditions, close to no cloud coverage, and a small T-air minus T-skin difference. It can also be inferred from Fig. 6c and d that the T-air minus T-skin difference is smaller for a cloudy day, even under low wind speed conditions.

Two days of mid-March and two days of early April were studied in Fig. 7. Figure 7a and b displays the first time when T-skin is the same as T-air under cloudy or non-cloudy conditions. Also, the daily temperature peak seems to move to sometime between 2:00–3:00 p.m. LT (Terra's ascending time over Caribou, ME). The two days of early April were selected because these were the last days when the National Environmental Satellite, Data, and Information Service (NESDIS) recorded cloud cover data for Caribou, ME. Data from early April (Fig. 7c and d) showcases the first time when T-skin is higher than T-air around 10:00 a.m.–12:00 p.m. LT. Hourly temperatures rise by approximately 10 °C when compared to mid-March, the peak is less significant, and moves closer to 3 p.m. LT. T-skin and T-air values are almost similar throughout a whole day. The diurnal cycle clearly shows that Terra and Aqua MODIS LST data will be higher correlated to the months of March and April for T-skin and T-air. The same cannot be said for the cold winter months of January and February. Wind speed and cloud cover's downward thermal flux clearly affect T-air and T-skin during the diurnal cycle.

5 Conclusions

Land Surface Temperature (LST) is the radiative skin temperature of the land surface. LST is determined by the land surface energy balance and varies rapidly because of the low thermal inertia of the land surface. LST may relate to the uppermost vegetation canopy or be a mixture of canopy and ground surface temperatures, depending on the region under observation. All of these surfaces have low heat capacity, so their temperatures respond rapidly to variations in incoming solar radiation due to cloud cover and 24 h temperature changes. However, in regions where snow is covering the land surface these processes vary slightly. Snow has a high albedo and reflects a significant amount of incoming radiation. This keeps the Earth's surface cooler than it otherwise would be, whereas a substance with a low albedo (like a forest) will reflect very little incoming radiation and absorb much of the energy. All else being equal, temperatures will be warmer over a low albedo surface than over a high albedo one.

In order to be able to monitor LST globally, satellite remote sensing is used given the scarcity of local stations. However, LST satellite readings have to be validated using ground-based estimates. This study assesses the efficacy of estimating LST using remotely sensed data from the MODIS instruments aboard satellites Terra and Aqua by comparing it with CREST-SAFE ground station (located in Caribou, ME) T-skin and T-air observations for the winters of 2013 and 2014. Caribou has a humid continental climate and offers fitting conditions for snow studies. The cold season has an average daily high temperature below 0 °C and lasts from mid-December to early March. Snow cover commonly withstands from mid-November to early April.

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The study showed that near surface air temperature is commonly higher than snow skin temperature on a daily average basis. Whenever there is no cloud cover, the radiative cooling of the ground resulted in lower T-skin and larger T-air minus T-skin differences. A negative trend indicated that the T-air minus T-skin difference is inversely proportional to cloud cover. However, this temperature difference distribution is not clustered and it is not affected exclusively by cloud cover. Wind speed plays an important role as well.

Linear correlation comparisons between both T-skin and T-air with MODIS (Terra and Aqua) LST readings showed that higher correlation exists between T-air and MODIS LST data. Furthermore, there are disparities between day-time and night-time correlations related to the radiative cooling of the snow. The T-air minus T-skin difference is mostly driven by the radiative cooling of the land surface whenever clouds are non-existent. The presence of clouds provides a significant downward thermal flux that heats the surface and helps decrease the T-air minus T-skin difference. Since satellite radiometry is applied to vast spaces that mainly comprise of various land and vegetation types, the surface properties at the region of study have to be as representative as possible of the land surface properties within the instrument's FOV. This is important because vegetation canopy temperatures are closer to the air temperature than to the LST. Also, higher wind speed conditions will always make the T-skin and T-air values closely resemble each other.

It is important that the instruments aboard satellites read the true LST under the presence of snow because spring flood and avalanche warnings might be developed under these observations. If the snow cover temperature and wetness is going to be derived from the remotely sensed LST, these values cannot be off by 50 % or higher. This issue should be looked at because current LST satellite readings might need an additional consideration to obtain a better estimation when snow cover is present so that the physical processes of surface energy and water balance at local through global scales are defined correctly in order to better predict the ongoing and future global change. Additional insight might be drawn by only doing this same study for the spring

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months of March and April when snow cover is still present but T-skin and T-air are relatively similar to each other. Furthermore, the study can be refocused by examining the change of the MODIS LST with the fraction of forest within the sensor FOV. If the portion of forest cover within certain small area varies but T-skin and T-air do not, then a relatively smooth change of MODIS LST with forest fraction can be obtained. While there may be no fully forested or fully non-forested pixels, maybe supplementary LST estimates can be extrapolated to estimate LST to zero and 100 % forest fraction if there were relatively large range of forest fractions for which we have LST estimates. Maybe then these values can be compared with the T-skin observed at the station. Inversely, it can be examined whether the LST values extrapolated to 100 % forest fraction will better correlate with T-air.

Data availability

The ground-observed datasets used in this study are available at the CREST-SAFE website: http://noaacrest.org//snow/. The remotely-sensed satellite datasets can be accessed and downloaded from the National Aeronautics and Space Administration (NASA) MODIS website: http://modis.gsfc.nasa.gov/.

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Table 1. R^2 correlation coefficient values between MODIS (Terra and Aqua) LST data and the snow skin and air temperature values for the winters of 2013 and 2014 during day-time view.

Temperature	2013		2014	
	Terra	Aqua	Terra	Aqua
Snow Skin	0.78	0.79	0.45	0.82
Air	0.87	0.80	0.83	0.85

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Table 2. R^2 correlation coefficient values between MODIS (Terra and Aqua) LST data and the snow skin and air temperature values for the winters of 2013 and 2014 during night-time view.

Temperature	2013		2014	
	Terra	Aqua	Terra	Aqua
Snow Skin	0.30	0.59	0.71	0.82
Air	0.43	0.65	0.78	0.86

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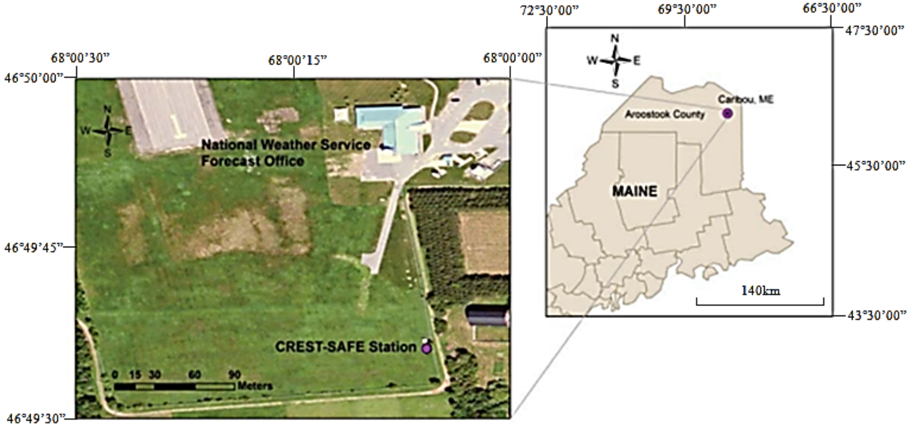

Figure 1. CREST-SAFE location (source: Lakhankar et al., 2013).

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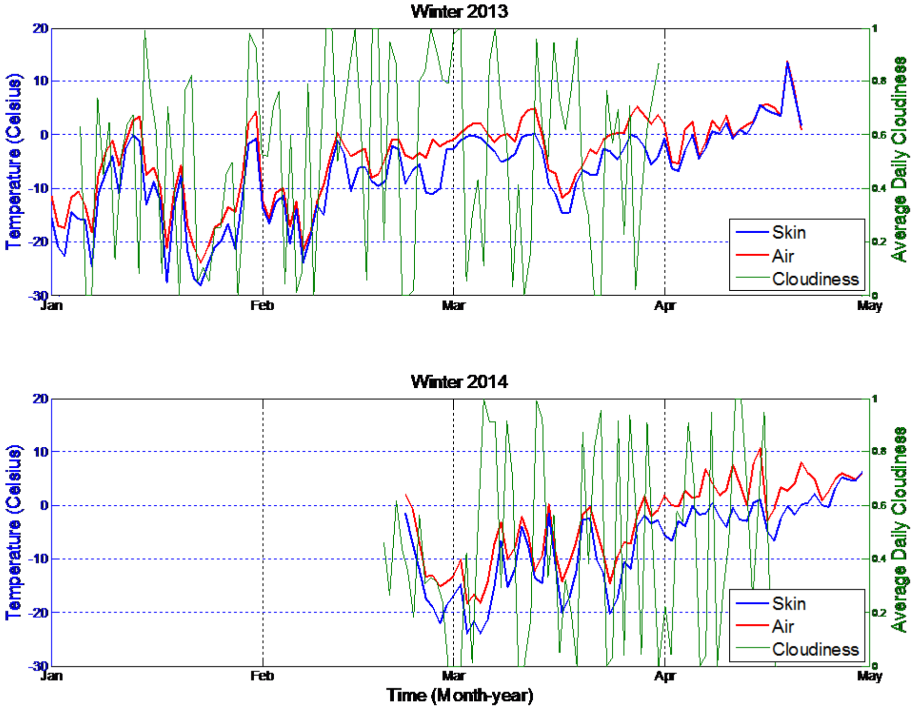

Figure 2. Snow skin and air temperature daily data curves for the winters of 2013 and 2014.

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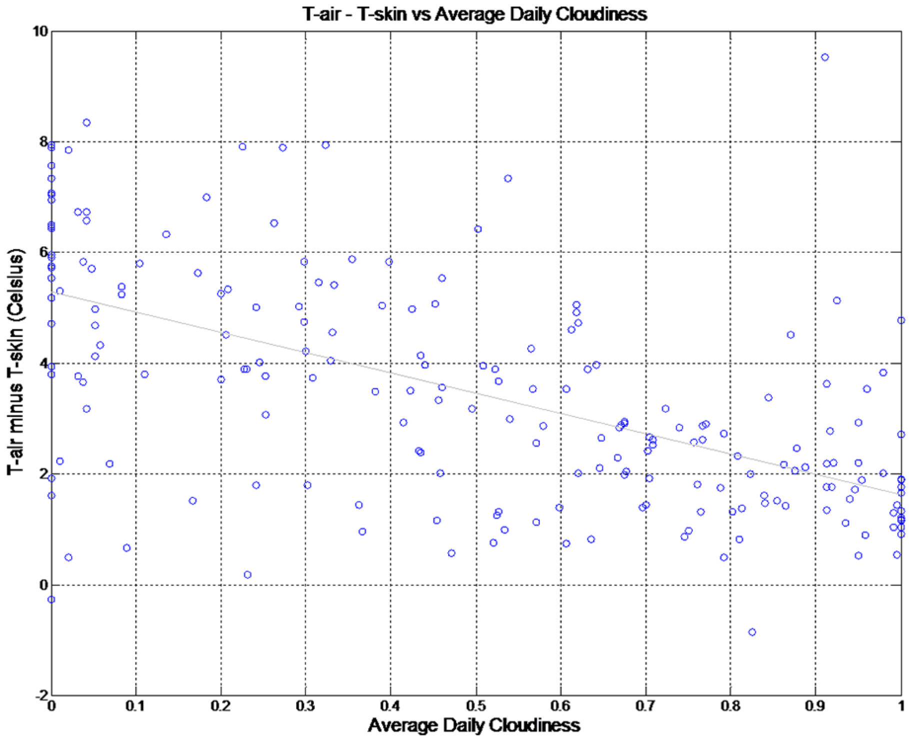

Figure 3. Average daily cloudiness vs. air minus snow skin temperature difference (T-air – T-skin) clustering by air temperature ranges.

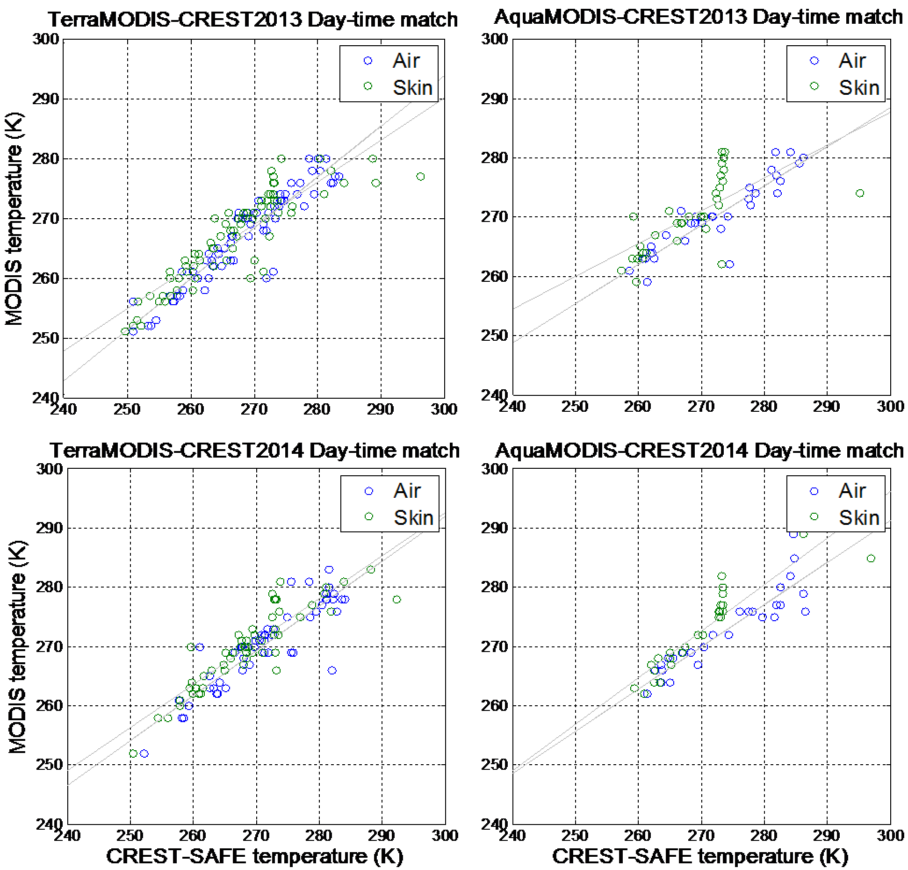

Figure 4. In-situ snow skin and air temperature data comparison with MODIS (Terra and Aqua) LST day-time data and correlations for winters 2013 and 2014.

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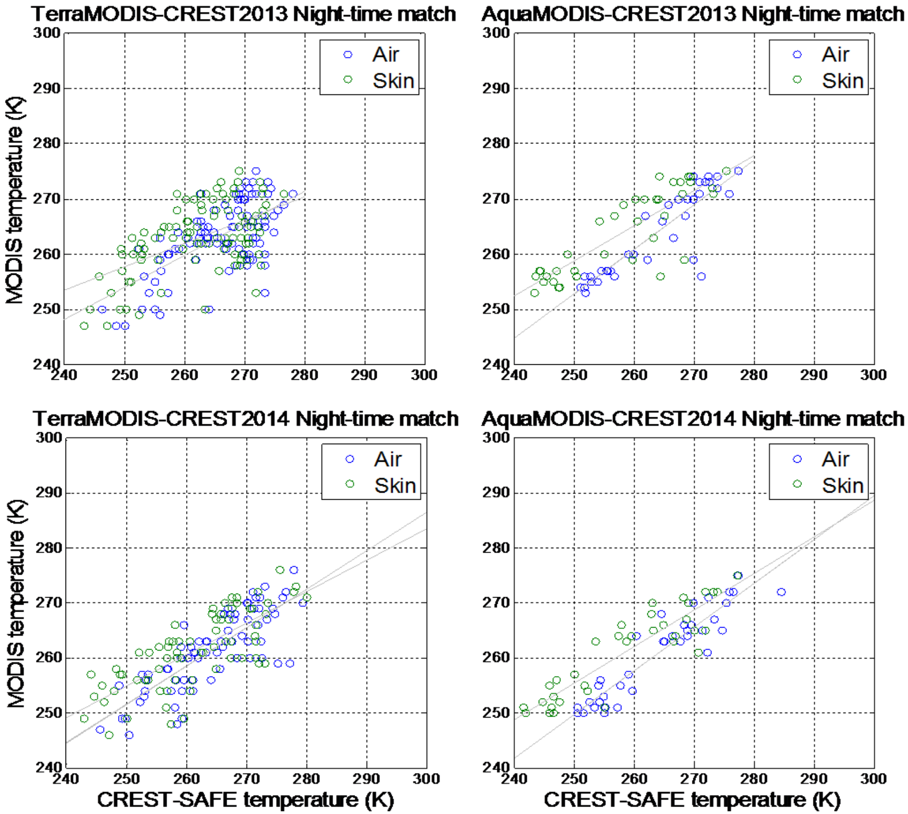

Figure 5. In-situ snow skin and air temperature data comparison with MODIS (Terra and Aqua) LST night-time data and correlations for winters 2013 and 2014.

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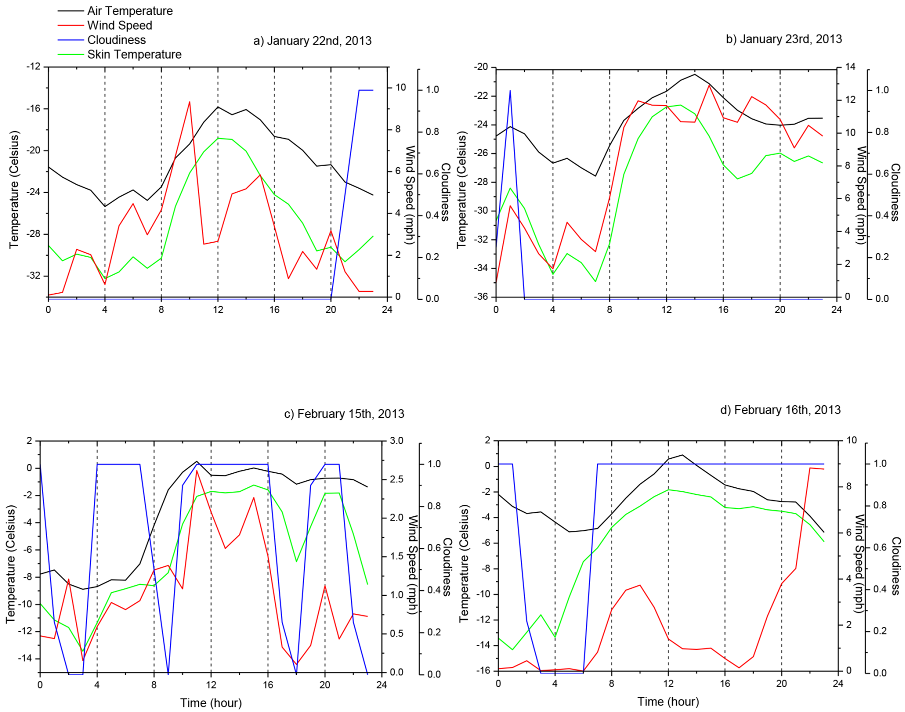

Figure 6. Snow skin and air temperature hourly values at the CREST-SAFE station in Caribou, ME for the days of 22–23 January (**a** and **b**) and 15–16 February (**c** and **d**) of winter 2013.

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Near–surface air temperature and snow skin temperature comparison

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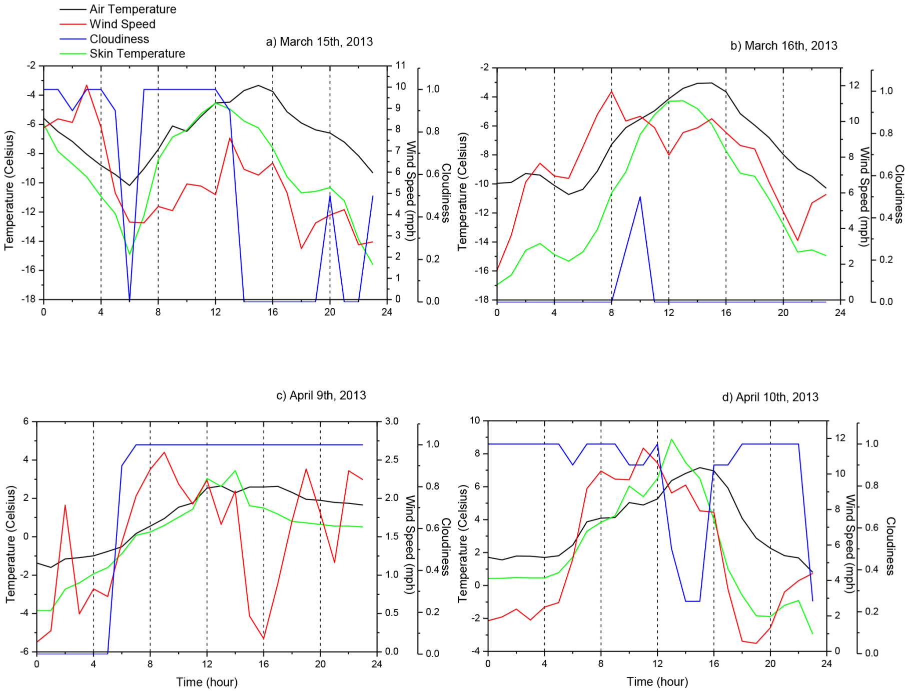

Figure 7. Snow skin and air temperature hourly values at the CREST-SAFE station in Caribou, ME for the days of 15–16 March (**a** and **b**) and 9–10 April (**c** and **d**) of winter 2013.

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