Evaluation of analytical models for surface temperature differences in sun and shade with field data

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1. Introduction

Analytical models have been developed to predict the temperature difference between sunlit and shaded regions. The models were developed in order to gain insight into the influence and sensitivities of various parameters and processes on temperature differences. The models also provided guidance during the development of numerical predictive methods.

The development of the analytical models assumes two adjacent ground surface locations; one in full sunlight and one in complete shade. The locations are assumed to be identical in the sense that they have the same conditions with respect to moisture status, soil properties, amount and type of vegetation, and climatic conditions. The models are based on the energy balance at the soil or rock surface:

$$Rn = LE + H + G \qquad (1)$$

where Rn is the net radiation flux, LE is latent heat flux, H is the sensible heat flux, and G is the ground heat flux.

Three models of temperature differences between sunlit and shaded surfaces were developed. First, a model without soil moisture was developed. This allowed the latent heat flux term to be set to zero. This model may be applicable to very dry bare soil conditions, or where relatively intact rock is exposed on the surface. The second model includes soil moisture, expanding the capability of the model to include the bare soil with some moisture in the near-surface. The third model includes vegetation, permitting a mixture of bare soil and vegetation to be modeled. The intent of this model was capture the influence of relatively sparse vegetation on sun-shade temperature differences.

The models can only be considered approximate in nature due to the numerous assumptions and simplifications they contain; however, the models do provide some insight into how temperature differences in sun and shaded locations may be affected by near surface properties and conditions.

Data collected in the field were evaluated and compared to the predicted response from the analytical models. The purpose of the evaluation was to:

1. Evaluate ability of the analytical models to predict field values

2. Investigate sensitivities of temperatures to factors such as moisture status, wind speed, etc.

Each time field measurements were made, there was an opportunity to compare the measured values with those predicted using the analytical models. Input to the analytical models included date and time of day (for solar zenith angle calculation), and air temperature, relative humidity, and wind speed from the meteorological data available at the field test site. An important input parameter for which there was no measured value was albedo. In addition, some terms used in calculating the surface resistances such as roughness length were not measured.

The primary output from the models was the sun-shade temperature difference. In addition, the models provided predictions of the energy balance terms, such as the predicted net radiation, the soil heat flux, etc.

Generalizations regarding model capabilities include:

- The models usually predict the net radiation at the field site to within a few percent.

- The model output is quite sensitive to surface moisture and wind speed. The model is also sensitive to albedo and roughness length (a surface characteristic that is not well known).

- Model output that matches the measured data is to some extent non-unique. Different combinations of input parameters can yield predictions that are reasonably close to the measured data.

2. Evaluation of data from bare soil surface

On March 10, 2003, surface temperatures measured on a nearly bare soil surface exposed to sun and shaded conditions. Measurements of water content, soil water potential and thermal properties were made as a function of depth from the surface. Climatic data was also collected.

Some comments on the data used as input in the model follow. The surface water potential was very low (below the resolution of the measurement system), consistent with the appearance of the surface as quite dry. The moisture potential was <-85 MPa, which corresponds to a moisture factor of <0.54 in the simple model. In other words, the surface moisture factor could range from 0 to 0.54. The wind speed was recorded within about a minute of the measured surface temperatures. However, wind speed was observed to quite variable, and there is no certainty that the recorded value was the actual wind speed at the time of temperature measurement.

Model results are given in Figure 2 (solid lines) as a function of the moisture factor for three assumed wind speeds. The model utilized the measured thermal properties of the near surface soil. Also shown in the figure is the measured sun-shade temperature difference, and the region of possible moisture factors based on the field measurement. For the wind speed of 1.7 m/s, the corresponding moisture factor would be 0.3, a value consistent with the measured range.

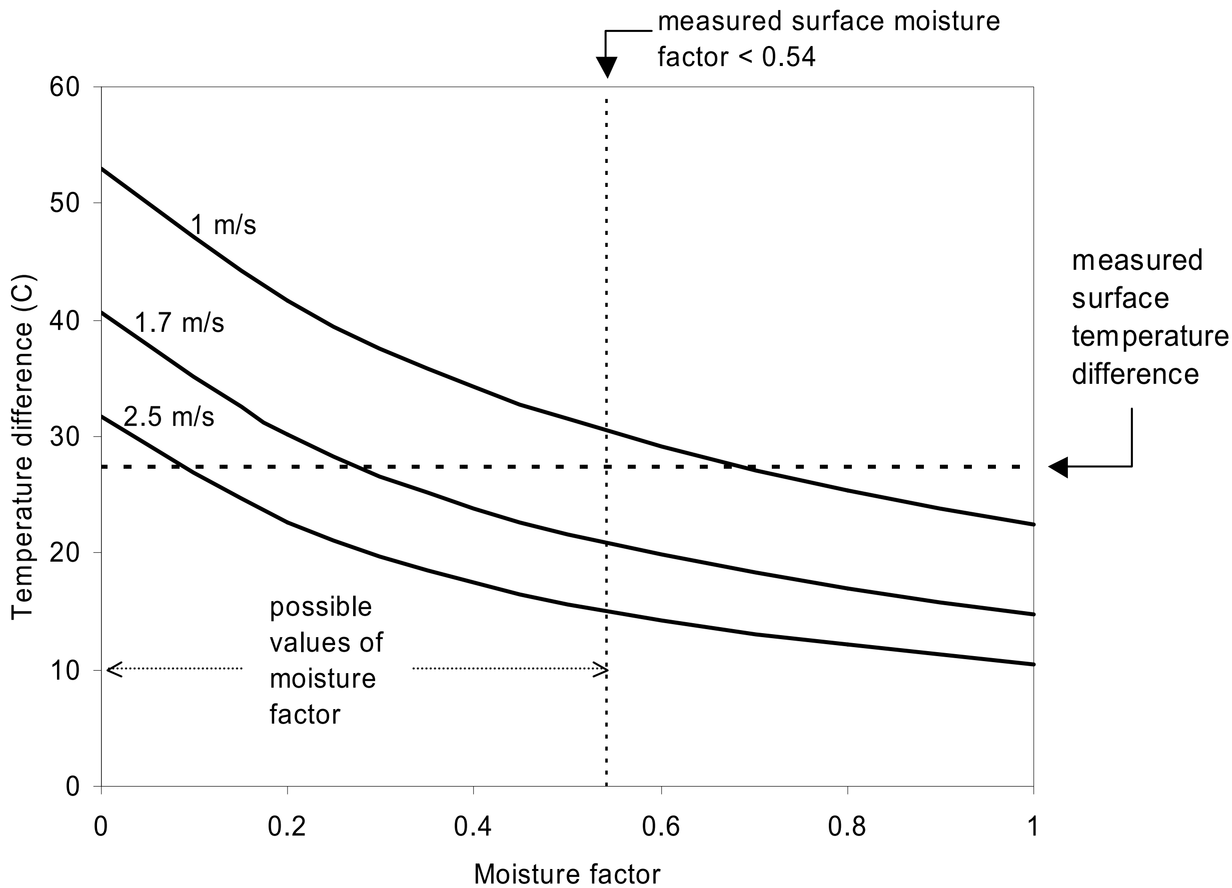

Figure 2 – Predicted temperature difference as a function of the moisture factor for three different wind speeds. Recorded wind speed was 1.7 m/s within about 1 minute of measurement. Measured surface temperature difference and moisture factor values are for bare soil at ALCD site on March 10, 2003.

On March 12, 2003, sun-shade temperature measurements were repeated. During these measurements, the wind speed varied noticeably. At the same time, the surface temperature was observed to change. (As expected, with increased wind speed, the surface cooled). Coincident with measurements of surface temperatures, qualitative estimates of the wind speed were made. These data are shown in Figure 3. Also shown in this figure is the model prediction (solid line) as a function of wind speed assuming a moisture factor of 0.3 (from the 3/10 data analysis). The model provides a reasonable estimate of the trend of the sun-shade surface temperature difference with wind speed.

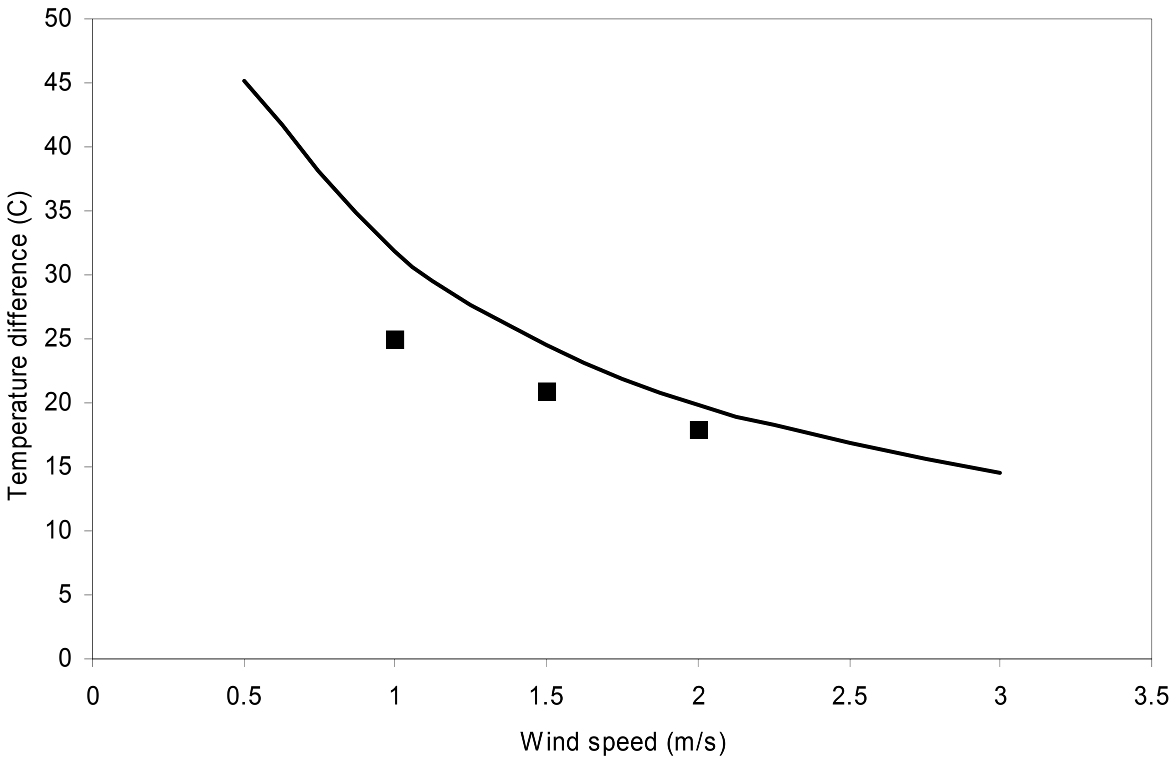

Figure 3 – Solid line is predicted temperature difference as a function of wind speed for bare soil with moisture factor of 0.3. Symbols denote measured temperatures at estimated wind speed on March 12, 2003 at ALCD site with bare soil.

3. Evaluation of data from stone covered surface

On March 12, 2003, sun-shade temperature differences were made on a surface comprised of stone of variable composition in the 2 to 10 cm size range. In constrast to the bare soil site, it was not possible to make independent thermal properties measurements with the Decagon thermal probe.

There was considerable variation in the surface temperature, especially in the sunlit area. Sun-shade temperature differences varied from 24 to 12 °C. As expected, dark colored stones tended to be warmer and have greater temperature differences. Two stones that exhibited much different surface temperatures, one dark and one light, were collected for cursory identification. The dark stone was identified as a basalt or andesite, and light colored stone identified as rhyolite with perhaps up to 20% quartz (Borns, personal communication).

In Figure 4 below, model prediction of surface temperature differences are calculated for the light colored stone (albedo=0.4) and the dark colored stone (albedo = 0.1) as a function of thermal inertia. These calculations assumed no moisture. For the measured temperature difference, the thermal inertia for the two albedos can be found. These values of thermal inertia are quite high (>2500 TIUs) even for intact rock, suggesting that the model is lacking with this surface condition. Inclusion of moisture (even though the surface of the stones was dry) and accounting for the rough surface in the energy balance may be ways of improving the model.

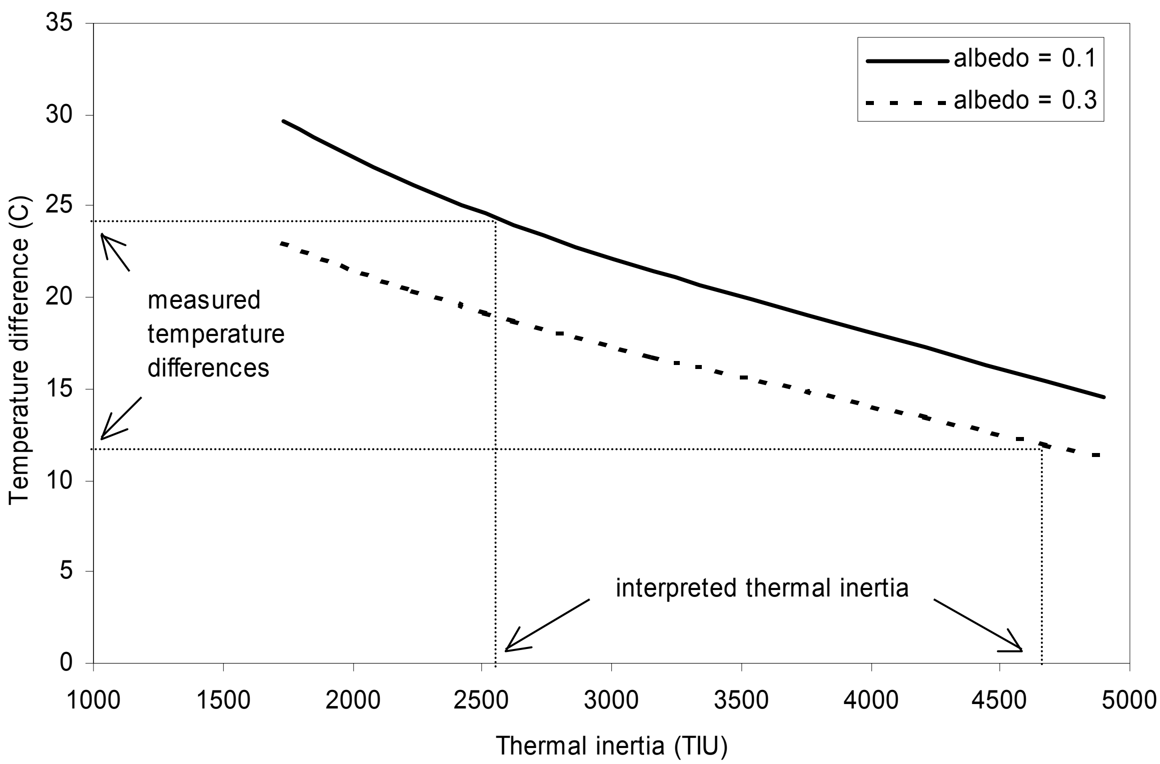

Figure 4 – Model prediction of sun-shade temperature difference as a function of thermal inertia for two different values of albedo, corresponding to light and dark colored stone. Field measured temperature differences and interpreted thermal inertia also given.

4. Evaluation of albedo from dry soil

The data from the dry soil in sun and shade lysimeters can be used to exercise the analytical model without including a latent heat flux. In particular, these data can be used to estimate the albedo of the dry soil surface. Model predictions corresponding to measurements made on April 11 and May 19 are given in the figure below as a function of albedo. The predicted temperature differences are greater for the April 11 date because the wind speed was less on this day. The measured temperature differences for these days are used to define an albedo for each day that results in a good match with the model. The interpreted albedos of about 0.3 and 0.35 are in the reasonable range based on the literature, but have not been confirmed by measurement.

The albedos should be the same on both days as the soil conditions were the same. Not unexpectedly, the results were very sensitive to the wind speed used in the models. For example, changing the wind speed in the May 19 simulation by 20% yields a good match to the April 11 albedo estimate.

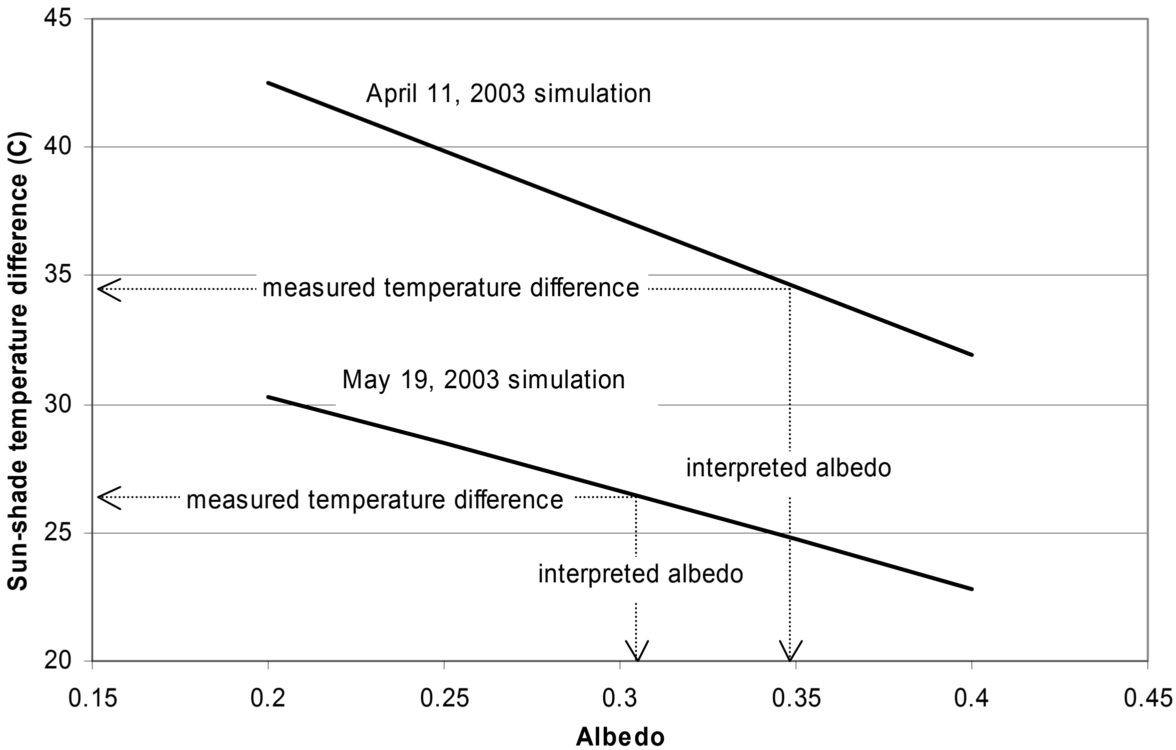

Figure 5 – Interpreted albedos for April 11 and May 19 measured temperatures by matching to model simulations for these dates with variable albedos (solid lines).

5. Evaluation of vegetation temperature differences

A limited number of measurements of sun-shade temperature differences of vegetation were made. The temperature varies considerably in the clumpy grass at the field site, and the minimum temperatures in the "heart" of the vegetation were recorded.

Date	Temperature difference (C)
March 12	10
May 19	8
June 16	16

The analytical model that includes vegetation was applied to the conditions of May 19. The model predicted temperatures ranging from 12 to 23 °C as the root zone moisture decreased from fully wet to the wilting point. This result suggests that the model predictions are in the range of the measured values. However, because the resistance model and the numerous vegetation parameters were taken from the literature, these results should not be viewed as verifying the model.

6. Discussion

The analytical models predict temperature differences that are consistent with those measured. This suggests the models capture much of the important behavior and processes that control the development of temperature differences.

At the same time, evaluation of the models with the field data reveals that there are so many unknowns (non-constrained input parameters) that it is not likely that predicted temperature differences can be used to extract precise thermal properties of surface materials. This suggests that pursuing empirical and/or comparative data analysis methods with the analytical models may be the most fruitful approach.

One of the most problematic aspects of the analytical models is the definition and parameterization of the resistances for soil and vegetation. Firstly, the model descriptions of the soil and vegetation resistances utilized in the analytical models were developed for specific applications and conditions, and they have not been verified or confirmed as being appropriate for the conditions under consideration here. Resistances are very difficult to measure, and thus it is very difficult to verify a resistance model. Secondly, the input parameters for the resistance models are not always well known or easy to determine. Wind speed is an important input parameter, but it should be measured locally which may be problematic at remote or hostile sites. The vegetation and soil resistances contain parameters that have been empirically derived from very limited data. Extrapolating these parameters to different conditions introduces more uncertainty. These considerations suggest that an approach that avoids explicitly describing resistances may be worthwhile.