THERMAL PARAMETERS EXTRACTED FROM DIURNAL CYCLES OF LAND SURFACE TEMPERATURE

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ABSTRACT

The diurnal and annual variation of land surface temperature (LST) are quantities which describe surface characteristics. Analyses of their long term changes allow to detect modifications of the land cover. By remote sensing the LST of large areas can be measured, but clouds generally prohibit the production of continuous LST maps. If cloud cover is brief, the discontinuous time series of cloudfree measurements still approximates a cloudfree diurnal temperature cycle (DTC). In order to interpolate the missing values and to describe the thermal behaviour of the land surface as a whole, advantage is taken of METEOSATs (MSGs) high temporal resolution of 30 minutes (15 minutes). A Levenberg-Marquardt minimisation scheme is utilised to automatically fit a model of the DTC to the time series of cloud-screened brightness temperatures (BT) or LSTs. Out of physical considerations and in order to stabilise the fits, a priori knowledge from solar geometry is utilised and the model function is required to be smooth and continuous. A robust estimator of the error, which is based on the median rather than the arithmetic mean, is used to lessen the impact of outliers on the fits. The thermal behaviour of the land surface is then described by the determined model parameters, and the 48 METEOSAT BTs (96 MSG LSTs) per pixel per day are reduced to 5 thermal surface parameters (TSP) per pixel per day. Monthly composites (e.g., maximum and median) of cloud-screened BTs (LSTs) yield synthetic DTCs, which are less influenced by synoptic effects. Fitting the model to monthly composites reduces the 17520 METEOSAT BTs (35040 MSG LSTs) per pixel per year to 60 TSPs per pixel per year.

1. INTRODUCTION

The temperature of land surfaces determines the energy exchange with the atmosphere; horizontal temperature differences are the main driving forces of local wind systems. The diurnal and annual variations of land surface temperature (LST) are related to insolation, wind, and to surface characteristics, e.g. vegetation, soil moisture, soil type, surface structure, etc. (Carlson and Boland, 1978; Price, 1985; Wetzel et al., 1984). Thermodynamic measurements at ground level are possible but for inhomogeneous land surfaces it is not at all clear how to measure LST, e.g. for a mix of roads, buildings, trees, parks, etc.. Only by means of remote sensing diurnal variations of LST of extended regions can be measured; LSTs represent effective, spatially averaged values of skin temperature over heterogeneous areas, which can be used to examine the modelling of the thermal forcing in mesoscale models (Carlson and Boland, 1978). A review of retrieval methods for LST and emissivity from passive sensor data is given by Dash et al. (2002).

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A remotely sensed quantity that is frequently used is the normalised difference vegetation index (NDVI); it was shown to correlate strongly to canopy properties such as the leaf area index, biomass, and fraction of vegetation cover. NDVI time series have been used to classify land cover at a global scale (Defries and Townshend, 1994); combining it with LST can improve classification, e.g. time series of the ratio between LST and NDVI are less influenced by interannual variations in climatic conditions than NDVI time series alone (Ehrlich and Lambin, 1996). Analyses of long term changes of LST and NDVI allow the detection of modifications of the land cover or tendencies towards desertification (Lambin and Ehrlich, 1996). The slope of LST vs. NDVI was found to be useful for the parameterisation of surface resistance in regional evapotranspiration research (Nemani and Running, 1989) and dependent on fractional vegetation cover (Smith and Choudhury, 1991). The slope of LST vs. NDVI also correlates strongly to crop-moisture index values indicating that LST/NDVI relationships can be used to infer surface moisture conditions (Nemani et al., 1993; Sandholt et al., 2002).

2. MODELLING OF DIURNAL TEMPERATURE CYCLES (DTC)

A model consisting of a harmonic and an exponential term is fitted to the diurnal temperature cycle (DTC) of the land surface, describing the effect of the sun and the decrease of the surface temperature at night, respectively (Göttsche and Olesen, 2001). The modelling yields thermal surface parameters (TSP) which describe and summarise the DTC and can be used to interpolate missing data, e.g. due to technical problems or brief cloud cover (Schädlich et al., 2001). The TSPs depend on all modelled temperatures and are, thus, hardly influenced by outliers. This improves the determination of the minimum / maximum temperature of the DTC, which is important for the calculation of thermal inertia. The choice of the harmonic term is based on the solution of the equation of thermal diffusion. The exponential term was chosen because it is typical for natural decay-processes, e.g. as described by Newton’s law of cooling. This semi-empirical approach leads to the following, descriptive model:

\[
\begin{align*}
T_1(t) &= T_0 + T_a \cdot \cos\left(\frac{\pi}{\omega} \cdot (t - t_m)\right) \\
T_2(t) &= (T_0 + \delta T) + \left[ T_a \cdot \cos\left(\frac{\pi}{\omega} \cdot (t - t_m)\right) - \delta T \right] \cdot e^{-\frac{(t-t_s)}{k}}
\end{align*}
\]

(1)

The TSPs in equation 1 are explained in Table 1 and illustrated in Figure 1; \(T_{1,2}\) is the temperature in the respective parts of the model. The model assumes clear-sky conditions (cloud-screened pixels) without significant changes in wind-speed, that only one sunrise takes place, and that the temperature decays freely after the “thermal sunset” defined by \(t_s\). Therefore, time \(t\) is limited to the interval between two successive sunrises (48 and 96 slots for METEOSAT and MSG, respectively).

![Figure 1. METEOSAT brightness temperatures (red boxes) measured over a desert pixel (Tunisia) and the modelled DTC (blue line). The model is given by equation 1 and the TSPs are explained in Table 1.](image-url)
<table>
<thead>
<tr>
<th>TSP</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$ [°C]</td>
<td>Residual temperature (~ sunrise)</td>
</tr>
<tr>
<td>$T_A$ [°C]</td>
<td>Temperature amplitude</td>
</tr>
<tr>
<td>$\omega$ [hh:mm]</td>
<td>Width over ±$\pi$/2 (period/2) of cosine-term</td>
</tr>
<tr>
<td>$T_M$ [solar time]</td>
<td>Time of the maximum</td>
</tr>
<tr>
<td>$T_S$ [solar time]</td>
<td>Start of the attenuation function</td>
</tr>
<tr>
<td>$K$ [hh:mm]</td>
<td>Attenuation constant</td>
</tr>
<tr>
<td>$\delta T$ [°C]</td>
<td>$T_0 - T(t \to \infty)$, where $t$ is the time</td>
</tr>
</tbody>
</table>

Table 1. The meaning of the TSPs shown in Figure 1.

In practice only 44 METEOSAT slots are used (from 6 hours to 4 hours of the next day) to avoid influence of the previous cooling phase and the next sunrise on the fits. Residual temperature $T_0$ is an extrapolated value: it describes the lowest early morning temperature, which lies outside the modelled interval. From spring to autumn and for moderate northern latitudes $T_0$ lies outside the chosen interval by usually less than 1 hour. It is straightforward to choose or to automatically determine an appropriate interval for other latitudes. The model of the DTC given by equation 1 is non-linear, which means that the corresponding normal equations cannot be solved explicitly. Therefore, a Levenberg-Marquardt scheme is utilised to fit the model to the time-series of BTs (LSTs). The approach works on a pixel basis; thus, it allows the automatic calculation of TSPs for data of arbitrary size, i.e. time-series of complete METEOSAT (MSG) images. Ideally, the thermal behaviour of each pixel is characterised by its respective set of TSPs. However, with the initial model given by equation 1 some of the retrieved TSPs had errors of more than 90 % even for cloudfree days. Especially the values determined for the residual temperature $T_0$ tended to be unrealistically low. In order to improve the method the following alterations were introduced:

- The width of the cosine $\omega$ is calculated from astronomical parameters (daylight hours).
- The model is required to be differentiable at the boundary between the cosine and the attenuation function with this constraint the attenuation constant $k$ can be calculated.
- Furthermore, a robust estimator of the error function is used to reduce the effect of outliers.

With these improvements the modelling was stable for all meaningful conditions; furthermore, two TSPs less have to be determined by fitting. The long term thermal behaviour of land-surfaces, e.g. seasonal change, is then described by the variation of the TSPs in time. The method is superior to minimum / maximum temperature schemes, because theoretically no information is lost during parameterisation. Small gaps due to clouds as well as outliers due to undetected clouds are smoothed by the modelling.

3. BEST-DAYS AND MEDIAN COMPOSITES

DTCs of individual days are influenced by the current and the previous synoptic situation, e.g. by the cloud situation and the surface-moisture. On the other hand, also more permanent surface properties, e.g. vegetation and soil type, are to be derived from the temperature cycle. In order to demonstrate the functionality and stability of the modelling approach, fits to two types of monthly composites are performed:

- “Best-days” composite: those DTCs per pixel and composite interval, which a) have a reasonable distribution of cloudfree measurements and b) the highest number of cloudfree measurements. If two days have the same number of cloudfree measurements, the one with the highest LST is selected. In effect, best-days composites are a collection of the DTCs with the least cloud cover.
- Median composite: the median for each pixel location and slot in the composite-interval. At least four cloud-screened values are required in order to exclude the minimum and the maximum value. The DTCs derived from median composites approximate a cloudfree version of the most frequently encountered (typical) day in the composite-interval. Unlike the mean, the median is not an average: this is advantageous if only few values are processed, which possibly contain outliers. The median estimates the expectation value of the pixels and, thus, reduces navigation error if it is purely random.

Figure 2 to Figure 4 show results obtained for the “best-days” of June 1996; the data cover parts of northern Europe down to northern Africa. Due to the use of DTCs from different days of the month (see Figure 2) the TSP fields appear slightly “patchy”. Furthermore, the results are noisy due to missing data (cloud cover) in the individual DTCs. Figure 5 and Figure 7 show the TSPs for the corresponding median composite; these
are smoother and show more details. In order to demonstrate the effect of seasonal variation, TSPs from median composites of April and August 1996 (Figure 6 and Figure 8) are also shown.

Figure 2. Selected “best-days” in June 1996 (left), respective valid (=black) and invalid (=white) DTCs (centre), and maximum NDVI composite derived from NOAA/AVHRR data (data courtesy: D. Koslowsky, FU-Berlin). The variability of “best-days” is higher in the southern part of the data, which is due to the fact that more days fulfill the basic selection criteria (distribution of cloudfree measurements).

Figure 3. TSPs derived from “best-days” composite of June 1996 (see Figure 2). Residual temperature (left), temperature amplitude (centre), and maximum temperature (right). The three images reflect the different thermal characteristics of the surface. In the northern half of the data the maximum temperature seems to be less informative than the individual TSPs. Compositing effects are most apparent in the temperature amplitude.
Figure 4. TSPs derived from “best-days” composite of June 1996 (see Figure 2). Time of maximum temperature (left), starting time of attenuation function (centre), and attenuation constant (right). Due to noise only the southern half of the data appears to be useful.

Figure 5. TSPs derived from median composite of June 1996. Time of maximum temperature (left), starting time of attenuation function (centre), and attenuation constant (right). The TSPs are less noisy than for the “best-days” composite (Figure 4). The time of the maximum temperature appears to be meaningful for most of the data, e.g. for the salt-lakes in northern Africa, the Po-Valley, and the Friesian Low-lands.
Figure 6. TSPs derived from median composite of April 1996. Residual temperature (left), temperature amplitude (centre), and maximum temperature (right). Black pixels represent insufficient data. Residual temperature correlates strongly with elevation.

Figure 7. TSPs derived from median composite of June 1996. Residual temperature (left), temperature amplitude (centre), and maximum temperature (right). Black pixels represent insufficient data. The TSP fields are smoother and less noisy than for the corresponding “best-days” composite (Figure 3). Temperature amplitude is low for the Black Forest and the forests in the Vogese Mountains. Salt-lakes (northern Africa) can be seen in both TSPs but have a different spatial extent.
4. CONCLUSIONS AND OUTLOOK

A method to model DTCs of the land surface described by BT (LST) data from geostationary meteorological satellites has been introduced. The method allows a substantial amount of data reduction: using monthly composites the 17520 METEOSAT BTs (35040 MSG LSTs) per pixel per year can be reduced to 60 TSPs per pixel per year. This reduction makes a practical use of the data for long-term studies of land surface processes possible. Unlike simple composition-methods, e.g. maximum composites, the approach preserves most of the surface-related information content. For the geographical area given above, the fitting of the model to METEOSAT BTs was stable for all investigated monthly “best-days” and median composites (March to October 1996). For median composites, the “corrected” residual temperature $T_0 + \delta T$ and the corrected amplitude $T_a - \delta T$ are also promising candidates for land-cover change analyses, because $T_0 + \delta T$ can be determined more precisely than $T_0$. In dry areas the time of the maximum temperature $t_m$ and the attenuation constant $k$ can be used to characterise the land surface as well. The TSP fields have no or only few gaps due to clouds. A possible application of the scheme is cloud detection, e.g. the identification of partial cloud cover could be improved using dynamic thresholds based on model values. If one assumes that the shape of the cycles is preserved when LST instead of BT is used, the model can also be used to interpolate temporally sparse atmospheric corrections (Schädlich et al., 2001).

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5. REFERENCES


