A SIMPLE PHYSICALLY BASED MODEL OF DIURNAL CYCLES OF LAND SURFACE TEMPERATURE

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Abstract

Land surface temperature (LST) derived from MSG-SEVIRI data is one of the operational products of the Land Surface Analysis – Satellite Application Facility (LSA-SAF). The LSTs have a temporal resolution of 15 min and a sampling distance of 3 km at nadir, but due to clouds there are few days with complete diurnal temperature cycles (DTC) over larger continuous areas (so called "golden days"). Consequently, LST fields are generally discontinuous in time and space, which is rather restrictive for many applications. However, SEVIRI's high temporal resolution can be exploited to temporally interpolate discontinuous LST and use the modelled LST to improve temporal compositing and cloud screening. Interpolating missing LST on an operational basis requires a sufficiently simple DTC model. The model was designed using a minimum amount of ancillary data, is based on the surface energy balance, and accounts for atmospheric attenuation of solar irradiation. Its parameters (residual temperature, temperature amplitude, day-to-day change of residual temperature, time of maximum, start of attenuation function, attenuation constant, total optical thickness) are determined by fitting. The parameters summarize the thermal behaviour of the land surface and are more indicative of surface type and state (e.g. moisture) than individual LST. The model is evaluated with ground radiometric measurements from a permanent validation station near "Gobabeb Training and Research Centre", Namibia. Compared to an earlier version of the DTC model the new model shows improved performance especially during early morning. DTC variability is reproduced with an accuracy better than the accuracy of the LST itself. Thus the model can improve LST determination by reduction of noise and by removing undetected clouds.

INTRODUCTION

Satellite based remote sensing is the only realistic means by which the land surface can be monitored frequently and on large scales. The last decades have seen a steady increase of space-borne sensors with ever increasing capabilities with respect to spectral, spatial, and temporal resolution, e.g. compared to its predecessor the data volume produced by Meteosat Second Generation (MSG) has risen from 1 Terabyte to 20 Terabyte per year. This increase in data volume requires more automated data processing as well as algorithms capable of extracting and summarizing relevant information.

There are various approaches to derive LST from satellite based thermal infrared radiance (TIR) measurements. The approaches mainly differ in the assumptions they make to solve the underdetermined problem of simultaneous LST and emissivity retrieval (Dash et al., 2002). The diurnal and annual variations of LST are related to insolation, wind, and to surface characteristics, e.g. vegetation, surface moisture, surface type, surface structure, etc. (Carlson and Boland, 1978; Price, 1985; Wetzel et al., 1984). The daily variation of land surface temperature (LST) is mainly caused by solar irradiation, the land surface's main heating source. Göttsche and Olesen (2001) developed a simple physics-based model of cloud-free DTC describing the thermal behaviour of the surface (hereafter referred to as "Goe2001"), which several authors successfully used to interpolate atmospheric corrections and missing LST derived from satellite data (Schädlich et al., 2001; Jiang et al., 2006; Inamdar et al., 2008, Inamdar and French, 2009). However, Goe2001 did not account for the dependence of relative optical air mass on zenith angle and of atmospheric transparency on aerosols and dust, which reduce the amount of solar energy reaching the surface and alter its form from pure cosine (Watson and Hummer-Miller, 1981; Legrand, et al., 1989; Cautenet, et al., 1992; Legrand, et al., 1992). Motivated by these considerations Göttsche and Olesen (2009) developed the "Goe2008" model, which accounts for atmospheric attenuation of solar irradiation. With the new model the deviation between modelled and measured LST is substantially reduced and the observed variability of DTC width and slope is reproduced more realistically. The model can also be directly applied to LST derived from MSG/SEVIRI and allows the extraction of the thermal parameters over large areas.

DIURNAL TEMPERATURE CYCLE MODELS

The original DTC model of Göttsche and Olesen (2001) uses a cosine and an exponential term to describe the effect of the sun and the decrease of surface temperature at night, respectively:

$$\left.\begin{aligned} T_1(t) &= T_0 + T_a \cdot \cos\left(\frac{\pi}{\omega}\cdot(t - t_m)\right) \end{aligned}\right\} \quad t < t_s$$

$$\left.\begin{aligned} T_2(t) &= (T_0 + \delta T) + \left[T_a \cdot \cos\left(\frac{\pi}{\omega}\cdot(t_s - t_m)\right) - \delta T\right]\cdot e^{\frac{-(t-t_s)}{k}} \end{aligned}\right\} \quad t \geq t_s \qquad (1)$$

The parameters in equation 1 are explained in Table 1 and their effect on the equation is illustrated in Figure 1. Furthermore, Göttsche and Olesen (2001) identified the model parameter "width" with the daily duration of energy input by the sun, i.e. the hours of daylight. The choice of the harmonic term was based on the solution of the equation of thermal diffusion (Carslaw and Jaeger, 1959; Cracknell and Xue, 1996). The exponential term was chosen because it is typical for natural decay-processes, e.g. as described by Newton's law of cooling. The model described by eq.1 is required to be differentiable at $\mathbf{t_s}$. From this requirement attenuation constant k can be calculated (Göttsche and Olesen, 2001).

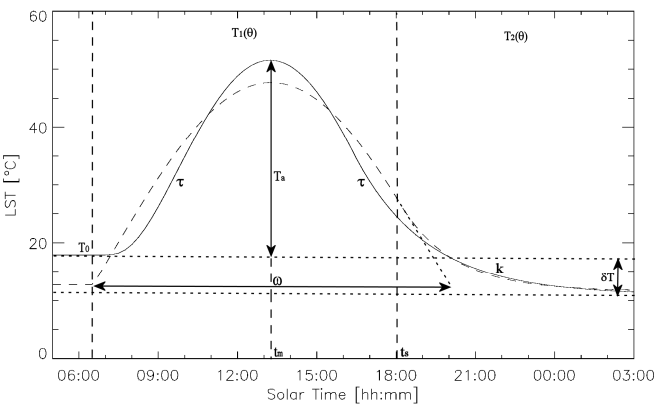

Figure 1: **Model parameters (Table 1) of DTC models "Goe2001" (broken line, eq. 1) and "Goe2008" (solid line, eq. 2). "Daytime" part T_1 (sunrise to start of attenuation function at t_s) and "night-time" part T_2 (t_s to end) are indicated by broken vertical lines.**

Parameter		*Meaning*
T_o	*[°C]*	residual temperature
T_a	*[°C]*	temperature amplitude
t_m	*[solar time]*	time of the maximum
t_s	*[solar time]*	start of the attenuation function
δT	*[°C]*	$T_o - T(t\rightarrow\infty)$, where t is time
ω	*[hh:mm]*	half-period of oscillation of cosine
k	*[hh:mm]*	attenuation constant (calculated)
τ		total optical thickness (TOT)

Table 1: **The meaning of the Goe2001 and Goe 2008 model parameters (see eqs. 1- 3).**

Figures 2 and 3 give examples of residual temperature and temperature amplitude, respectively; both quantities were determined using the Goe2001 TSP model and are given w.r.t. model temperatures at time $t\rightarrow\infty$. The input consisted of median LST composites derived by LSA-SAF from MSG/SEVIRI for the decade 11.-21.06.2009. For most areas shown in figures 2 and 3 parameters could be obtained. The figures demonstrate the ability of the approach to obtain smooth parameter fields over large areas; particularly residual temperature (fig. 2), which can be thought of as minimum LST composite for the 10 day period, is difficult to obtain without modelling, since a direct extraction via minimum composites would aggregate undetected clouds. Areas with high temperature amplitudes in figure 3 point towards surface covers with little resistance to temperature change and/or a low albedo, i.e. which have small thermal inertia and low evapotranspiration and strongly absorb solar energy. In the north-eastern part there are some data gaps (white areas) due to missing LST; this is caused by frequent clouds over the entire decade and indicates that the composition period should be increased, e.g. to 20 or 30 days, thus accepting a stronger smoothing of the annual cycle.

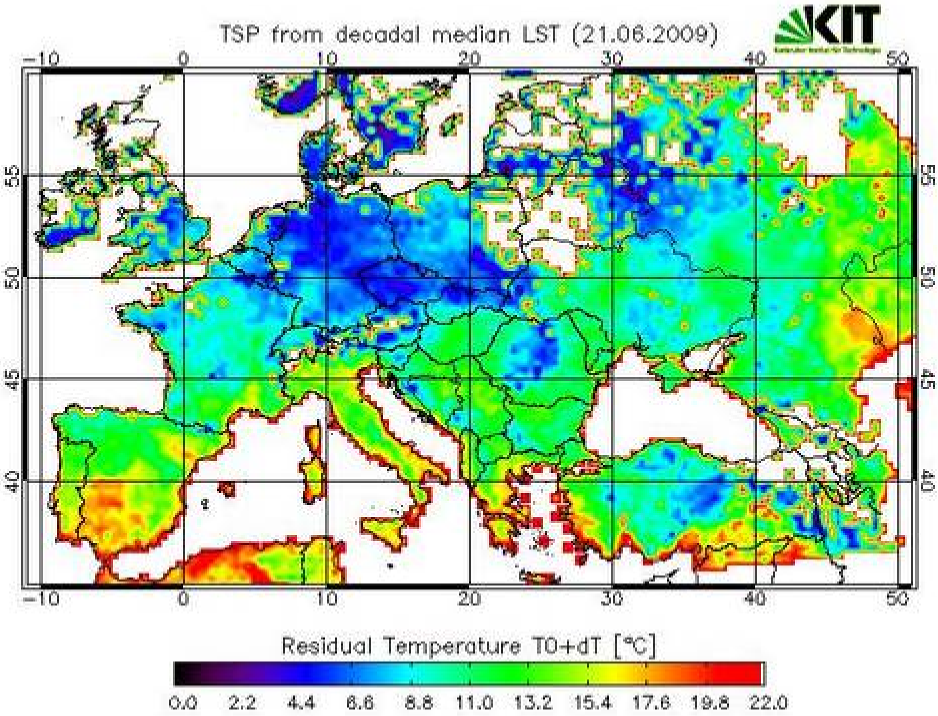

Figure 2: **Residual temperatures determined with Goe2001 from median composite LST (period 11.-21.06.2009). The temperatures are w.r.t. to modelled final temperatures (white: missing values). Data courtesy: LSA-SAF.**

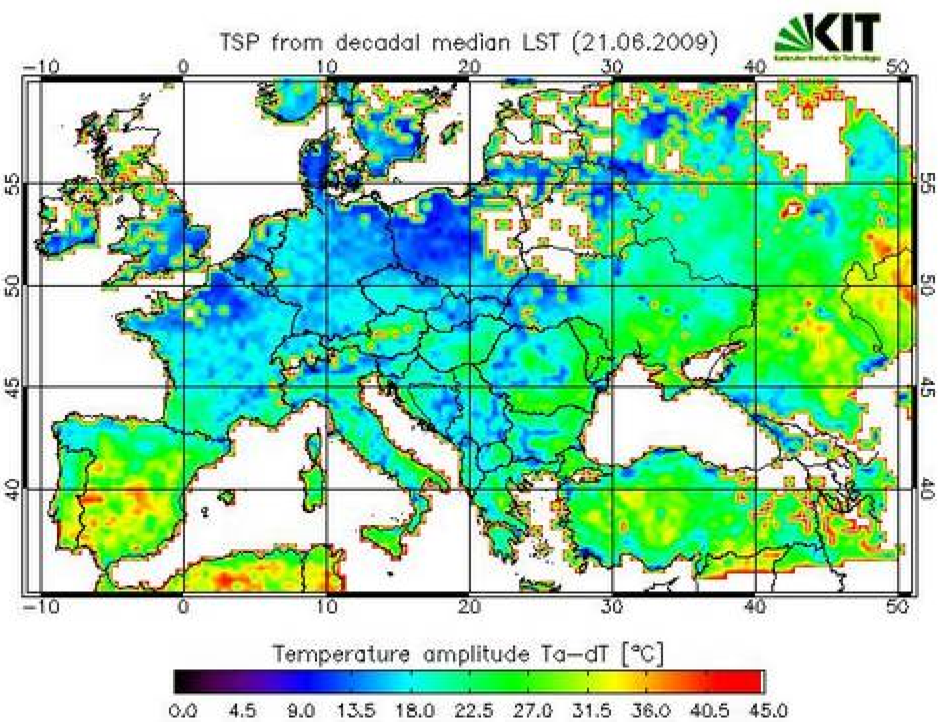

Figure 3: **Temperature amplitudes determined with Goe2001 from median composite LST (period 11.-21.06.2009). The temperature amplitudes are w.r.t. to modelled final temperatures (white: missing values). Data courtesy: LSA-SAF.**

The Goe2008 model is based on the surface energy balance equation (Göttsche and Olesen, 2009); its dependence on solar zenith angle follows naturally from the dependence on solar irradiation. The effect of atmospheric attenuation on solar irradiation is modelled using total optical thickness (TOT), which leads to a dependence on relative air mass. As in the Goe2001 model, Goe2008 and its first derivatives are assumed to be continuous at hour angle θ_s (end of cosine term and start of exponential decay). In equation 2 the subscripts "z" and "min" indicate zenith angle and minimum, respectively:

$$\left.\begin{aligned} T_1(\theta) &= T_0 + T_a \cdot \cos(\theta_z) \cdot \frac{e^{\tau(m_{\min} - m(\theta_z))}}{\cos(\theta_{z,\min})} && \theta < \theta_s \\ T_2(\theta) &= (T_0 + \delta T) + \left[T_a \cdot \cos(\theta_{zs}) \cdot \frac{e^{\tau(m_{\min} - m(\theta_{zs}))}}{\cos(\theta_{z,\min})} - \delta T \right] \cdot e^{\frac{-12h}{\pi k}(\theta - \theta_s)} && \theta \geq \theta_s \end{aligned}\right. \tag{2}$$

Attenuation constant k of the exponential decay follows from differentiability at θ_s:

$$k = \frac{12h}{\pi \cdot \dfrac{d\theta_z(\theta_s)}{d\theta}} \cdot \frac{\cos(\theta_{zs}) - \dfrac{\delta T}{T_a} \cdot \dfrac{\cos(\theta_{z,\min})}{e^{\tau(m_{\min} - m(\theta_{zs}))}}}{\sin(\theta_{zs}) + \tau \cdot \cos(\theta_{zs}) \cdot \dfrac{\partial m(\theta_{zs})}{\partial \theta_z}} \tag{3}$$

where the "simple" equation for air mass and its derivative w.r.t. solar zenith angle may be used:

$$m_{simple}(\theta_z) = \frac{1}{\cos(\theta_z)} \quad \text{and} \quad \frac{\partial m_{simple}(\theta_z)}{\partial \theta_z} = \frac{\sin(\theta_z)}{\cos^2(\theta_z)}$$

The derivative of solar zenith angle θ_z w.r.t. to hour angle θ is:

$$\frac{d\theta_z}{d\theta} = \frac{\sin(\theta) \cdot \cos(\delta) \cdot \cos(\phi)}{\sin(\delta) \cdot \sin(\phi) + \cos(\delta) \cdot \cos(\phi) \cdot \sin(\theta)}$$

The two DTC models given by equations 1 and 2 are 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 LST time-series, e.g. derived from radiometric measurements at Gobabeb validation station.

Initialisation of model parameters

The choice of initial parameter values is usually uncritical: width ω is not needed by the Goe2008 model since the duration of daylight is intrinsically included via zenith angle. Attenuation constant k is calculated once per iteration of the Levenberg-Marquardt minimisation scheme with equation 3, which simultaneously fits equations 2 to the data. T_o and T_a are initialised based on the maximum and minimum of the DTC. The other parameters are set to reasonable values, e.g. δT = 0.5 °C and t_m and t_s are set to 12:30h and 17:00h solar time, respectively. Atmospheric optical thickness is initialised with a representative value for "clear" atmospheres, e.g. $\tau = 0.03$.

GOBABEB VALIDATION STATION

Karlsruhe Institute of Technology (KIT) operates four permanent validation stations (1 x Portugal, 1 x Senegal, 2 x Namibia) for LST retrieved from TIR satellite measurements. The stations are part of the Land Surface Analysis – Satellite Application Facility (LSA-SAF) supported by EUMETSAT and their main objective is to validate LST derived from the Spinning Enhanced Visible and Infra-Red Imager

(SEVIRI) onboard MSG. The performance of the Goe2008 model is tested by fitting it to DTC collected during 2008 at the validation station "Gobabeb" (desert, Namibia). Gobabeb station's instruments are mounted at several heights of a 30m high wind profiling tower, which belongs to "Gobabeb Training and Research Centre" (23°33'S, 15°03'E, 408 m asl). The fields of view (FOV) of the two down-looking "Heitronics KT-15 IIP" radiometers on the gravel plain cover about 13 m^2 each. The research centre is located next to the Kuiseb River, which forms a natural boundary between large gravel plains and the vast sand dunes of the Namib Desert. The Kuiseb usually flows a few days per year and washes the advancing dunes into the South Atlantic Ocean, thereby stopping the sand from reaching the gravel plains. Gobabeb LST validation station is located on the large gravel plains about 2 km north-east of the Kuiseb and the research centre, thus being located in a highly homogeneous area.

RESULTS AND DISCUSSION

Figure 4 shows the results for the 13. December 2007: the two model fits are hardly discernable with the largest absolute differences (around 0.8°C) occurring in the afternoon (16:00h) and at sunrise (0.5°C). For the remaining part of this day both models fit the DTC equally well and have similar errors (around 0.6°C). The determined parameters (Table 2) are close to each other with the exception of T_o and δT. This is mainly due to the unrealistically steep slope of the Goe2001 model at sunrise, which is caused by modelling the solar heating flux as a pure cosine. Only LST from sunrise onwards were used, but the more slowly LST increases from sunrise, e.g. due to increased atmospheric attenuation, the more the Goe2001 model underestimates T_o. The "total optical thickness" determined by Goe2008 for this day is 0.033, indicating a clear atmosphere.

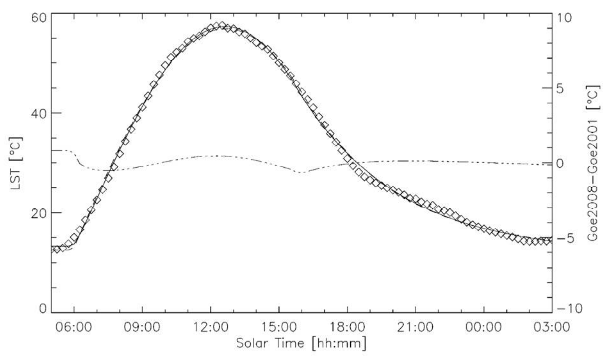

Figure 4: **Fits of Goe2001 (broken line) and Goe2008 (solid line) to LST derived from Gobabeb brightness temperatures on the 13. December 2007. The dash-dot line refers to the right axis and gives the difference between the two fits. The corresponding parameters and errors are given in Table 2.**

Parameter		*Goe2001*	*Goe2008*
T_o	*[°C]*	12.47	13.29
T_a	*[°C]*	44.41	44.02
t_m	*[solar time]*	12:40	12:38
t_s	*[solar time]*	16:06	16:04
δT	*[°C]*	-0.39	-1.72
ω	*[hh:mm]*	13:26	--:--
k	*[hh:mm]*	04:11	04:26
τ		--:--	0.033
mean error [°C]		0.60	0.55

Table 2: **Parameters determined with Goe2008 model from DTC measured on the 13. December 2007 at Gobabeb validation station (figure 4).**

Figure 5 shows fits of the two models to the DTC on 9. December 2007. Absolute differences between the models are up to 4°C at noon and 5.5°C in the morning. At night-time the two models are still in relatively good agreement, but there are still visible differences, e.g. 0.5°C at 03:00h. "Night-time" of Goe2001 is delayed by 1:35h compared to Goe2008. Table 3 gives a total optical thickness is 0.93, which corresponds to a transparency of around 40%. The determined times for maximum LST continue to agree well. The average error of Goe2001 is now 2.4°C, whereas it is still only 0.7°C for Goe2008.

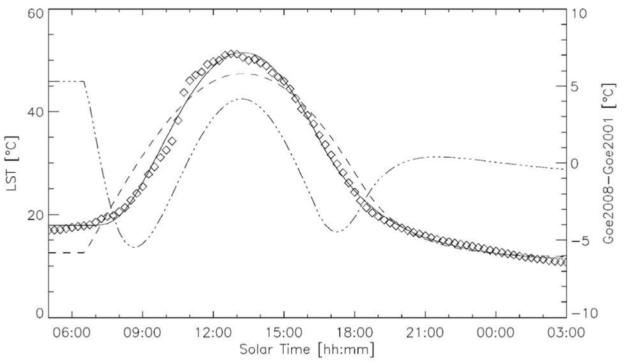

Figure 5: **Fit of Goe2001 (broken line) and Goe2008 (solid line) to LST derived from Gobabeb brightness temperatures on the 9. December 2007. The dash-dot line refers to the right axis and gives the difference between the two fits. The corresponding parameters and errors are given in Table 3.**

Parameter		***Goe2001***	***Goe2008***
T_o	***[°C]***	12.59	17.88
T_a	***[°C]***	34.81	33.66
t_m	***[solar time]***	13:16	13:14
t_s	***[solar time]***	18:16	16:41
δT	***[°C]***	-0.89	-6.99
ω	***[hh:mm]***	13:25	--:--
k	***[hh:mm]***	01:55	02:46
τ		--:--	0.929
mean error [°C]		2.38	0.72

Table 3: **Parameters determined with Goe2008 model from DTC measured on the 9. December 2007 at Gobabeb validation station (figure 5).**

The mean fit error (measured LST minus modelled LST) at 15 minutes interval for 54 days from Gobabeb is shown in Figure 6, i.e. each data point is the mean of 54 individual fit errors obtained at the corresponding solar time. Figure 6 shows that, on average, the Goe2001 model substantially underestimates the measured DTC around sunrise by 2.8°C and continues to either overestimate or underestimate the DTC until the afternoon, e.g. by 1.0°C around 13h. The considerably smaller values of the mean fit error of the Goe2008 model demonstrate its improved ability to reproduce the DTC. However, in the late afternoon the mean fit error oscillates with amplitude of 0.6°C, which suggests a relatively small, but systematic mismatch between model and measurements at this time of the day. At night time the two models show small and similar errors of less than 0.5°C.

The histogram in figure 7 represents the mean absolute deviations of Goe2008 per day for same 54 days as in Figure 6; it has a mean of 0.62°C and only 2 days deviate by more than 1°C. Furthermore, the histogram seems to indicate a bi-modal distribution with one peak near 0.5°C and a second one near 0.8°C: this is interpreted as overlapping distributions for clear-sky DTC and for DTC with regular disturbances (e.g. fog).

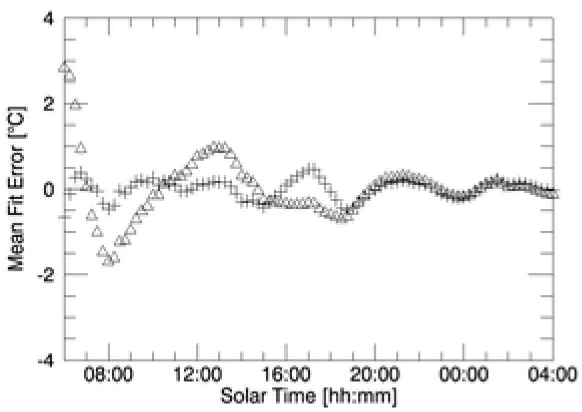

Figure 6: **Mean error at 15min interval over 54 days (05.12.2007 to 28.01.2008) between LST measured at Gobabeb and LST obtained from fitting with Goe2001 (triangles) and Goe2008 (crosses).**

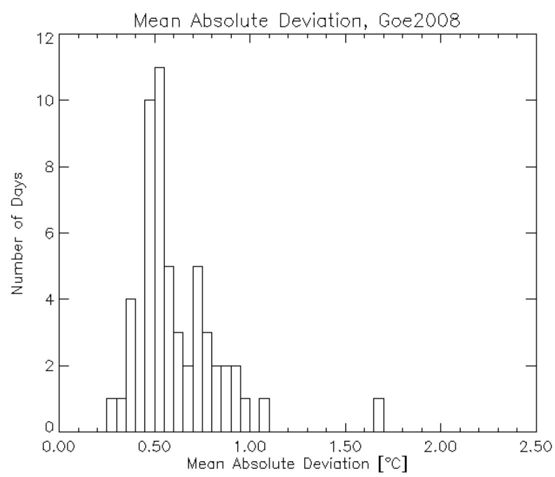

Figure 7: **Histogram of mean absolute deviation per day for Goe2008 fitted to 54 diurnal temperature cycles (days as in fig. 6) measured at Gobabeb, Namibia.**

CONCLUSIONS

Fitting a model to diurnal temperature cycles (DTC) summarizes the thermal behaviour of the land surface and yields representative and informative parameters: these can then be used to interpolate atmospheric corrections and missing land surface temperatures (Schädlich et al., 2001) or to improve cloud screening algorithms (Reuter, 2005; Huckle, 2009). The DTC model “Goe2008” is based on the surface energy balance equation; the cosine term of the model and its dependence on solar zenith angle follow naturally from the dependence on solar irradiation. Radiative cooling at “night-time” is modelled with an exponential decay function and daytime and night-time parts are required to smoothly fit together at “thermal sunset”, i.e. the model has to be differentiable. The effect of atmospheric attenuation on solar irradiation is modelled using total optical thickness (TOT), which leads to a dependence on relative air mass. However, the model does not require additional a priori information, naturally describes daytime LST with a cosine term, and links temperature amplitude to the solar constant, solar geometry, atmospheric attenuation, and to the thermal response of the surface to solar irradiation. The Goe2008 model also correctly reproduces the slow and smooth increase of LST around sunrise and the variable width of the DTC. A Levenberg-Marquardt minimisation scheme is used to fit the model to time series of LST, which are obtained from ground based thermal infrared (TIR) data measured at a permanent validation station near “Gobabeb Training and Research Centre”, Namibia. For clear-sky (nearly transparent) atmospheres the Göttsche and Olesen (2001) model and the new model have low average absolute errors of around 0.6°C; for turbid atmospheres with transparency of around 40% (based on determined TOT) the new model has up to three times lower average error. The performance of the models was investigated with 54 DTC from a validation site in an arid climate (Gobabeb, Namibia). The results demonstrate that new model has significantly lower mean of daily mean absolute deviation from measured DTC than the previous model (0.62°C vs. 0.85°C). However, the performance of the models depends on the quality of the LST as well as on atmospheric and surface wind conditions, i.e. the observed DTC should at least approximate undisturbed DTC. If such data are not available, temporal median or maximum LST composites can be used, as also demonstrated in this paper for the Goe2001 model currently implemented at the Land Surface Analysis - Satellite Application Facility (landsaf.meteo.pt). Finally, since total optical thickness is one of its parameters, the new DTC model may potentially benefit the determination of atmospheric dust loads over deserts.

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