MARS THERMAL MODEL FOR MEGA-PIXEL DIGITAL ELEVATION MODELS.

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Surface and subsurface temperatures can be modeled at high spatial resolution using Digital Elevation Models (DEMs). Volatiles are often associated with low temperatures, e.g., seasonal CO_2 frost in Martian gully alcoves or perennial water ice beneath pole-facing slopes. Thermal modeling of rough terrain is computationally challenging because of the large number of pixels and the non-local nature of horizons and the radiative heat fluxes between surface facets within view of each other. Here, a surface energy balance model is described that incorporates direct solar irradiance, terrain shadowing, (approximate) terrain irradiance, sky irradiance, and subsurface conduction. It is fast enough to be applied to DEMs that consist of over one million pixels and integrations over a million time steps.

The model is publicly available [1] and further described in Part 5 of the user guide that accompanies the online repository. It has been developed gradually over the last 20 years, with the 3D capabilities being the most recent addition. The topography is defined on a rectangular Cartesian grid aligned with the longitude and latitude directions, as is typical for gridded DEMs.

Terrain Shadowing: Shadowing by topography defines local horizons and is important for the surface energy balance. Horizons for each pixel are determined with azimuth rays, and the highest horizon in each direction is stored. For the purpose of horizon determinations, the topography is represented by triangular facets.

Use of a hierarchy of spatial grids with varying resolutions (multigrid method) dramatically accelerates the horizons calculation, because cells that are far from the point of interest are larger and fewer. For a domain with N pixels, the computational cost without multigrid method would be $O(N^2)$; with multigrid it is $O(N \log N)$, which makes it possible to calculate all horizons for mega-pixel DEMs on a single workstation.

Sky Irradiance: The model of atmospheric absorption and sky irradiance is based on the 0-dimensional model of Kieffer et al. [2]. It includes short-wave and long-wavelength sky irradiance.

In the literature various approximations for the sky irradiance are in use [3, 4]. One choice for the sky view factor is the spherical angle of the visible sky. The alternative is to weigh the diffuse sky irradiance with the cosine of the incidence angle. Both quantities can be calculated from horizon elevations. The results are close to the more elaborate short-wavelength scattering approximation obtained by [5].

Terrain Irradiance: The radiative flux between two surface facets within view of each other is described by a geometric "view factor". The current model implementation provides either full-fledged view factor calculations using a "slow" $O(N^2)$ algorithm or treats the terrain irradiance approximately, with $O(N)$ steps. The former is practically limited to about $N \approx 10^4$ pixels (on a single workstation), whereas the second can easily be used up to $N \approx 10^6$. The approximation assumes all land within view radiates at the same surface temperature, using a closed-form expression for the terrain irradiance in terms of horizon elevations. An algorithmically fast implementation of the terrain irradiance, that does not make this approximation, is currently under development [6].

Subsurface Heat Conduction: The model includes 1D subsurface heat conduction, using a Crank-Nicolson method with the Stefan-Boltzmann law as nonlinear boundary condition. This method is much faster than the simple explicit time step schemes used by most Mars thermal models. It has first been used in [7] and is described in Ref. [1] (Part 1). Lateral subsurface heat conduction is neglected.

Outline of Implementation: The model is written in Modern Fortran. Calculations proceed in two stages.

The first determines the horizons and, optionally, the view factors. This part is easily parallelized, as calculations for each pixel are independent of one another although the entire DEM has to be loaded into memory for each parallel job. One slice of the spatial domain is processed for each concurrent job.

The second part simulates the time evolution of illumination and surface temperature as the sun moves through the sky, using the horizons and, optionally, the view factors as input. The surface energy balance is integrated over time at steps of a fraction (e.g., 1/100th) of a solar day.

The model has been used in Ref. [8] with approximate terrain irradiance and Refs. [9, 10] with exact terrain irradiance. An example result is shown in Figure 1. Table 1 provides an overview of the program names and capabilities [1].

Discussion: A leading uncertainty for the accuracy of the model output turns out to be the thermal inertia input parameter, which is not known at high spatial resolution. Vice versa, the model can be used for thermal inertia mapping using THEMIS-IR nighttime surface temperatures combined with CTX-derived DEMs.

Suitable applications for the current implementation of the thermal model are DEMs at resolution coarser

Main program	Task	Terrain irradiance	Parallel	$O(N \log N)$ algorithm
`shadows`	pre-calculate horizons	N/A	yes	yes
`fieldofviews`	pre-calculate view factors	N/A	yes	no
`insol3d_mars`	direct insolation only, no atmosphere	no	no	yes
`insol3d_earth`	direct insolation only, Mauna Kea atm.	no	no	yes
`cratersQ_equilbr`	equilibrium solution for airless body	yes	no	no
`cratersQ_moon`	airless body	yes	no	no
`cratersQ_mars`	Mars orbit and atmosphere	approx.	no	yes
`cratersQ_mars_parallel`	Mars orbit and atmosphere	approx.	yes	yes
`cratersQ_mars_full`	Mars orbit and atmosphere	yes	no	no

Table 1: Overview of current implementations [1], directory `Topo3D/`.

than the scale for lateral heat conduction $\gtrsim$ 5 m/px (e.g., CTX-derived DEMs) and domains small enough to neglect changes in latitude and longitude, $\lesssim$ 60 km. DEMs with over 10^6 pixels have been modeled on a single workstation [8] (Fig. 1), and larger pixel dimensions can be processed on a computer cluster. Other 3D thermal or illumination models have been developed for airless bodies [e.g., 11, 12, 6]. The niche for the present model are Mars site studies with gridded DEMs. The model can be applied to the study of numerous potentially temperature-dependent processes, such as ice retreat, glacial flow, gully activity, slope streaks, seasonal CO_2 frost, and thermal inertia mapping.

Among desired improvements are a pipeline for thermal inertia inversions, vertically stratified thermal properties optimized with regards to memory-CPU bandwidth, 3D equilibrium ice table calculations, interfacing with a more advanced atmospheric model, and extension to paleoclimate conditions.

References

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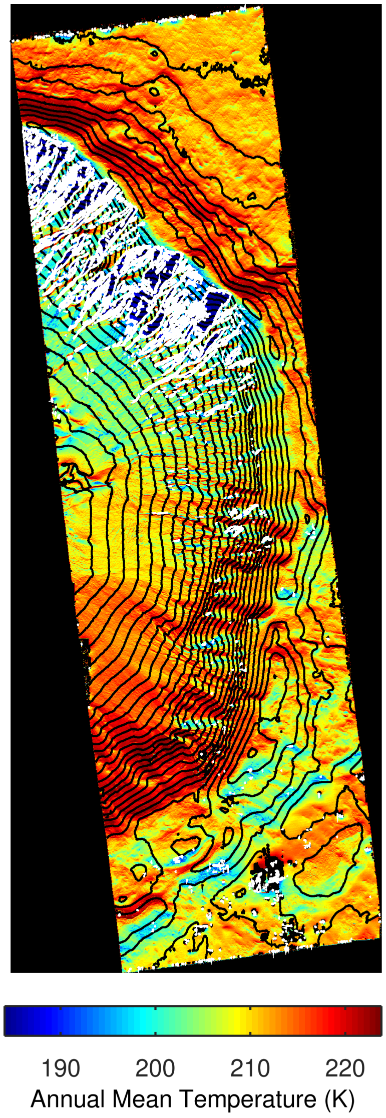

Figure 1: Results of a thermal model calculation with 1.4 million valid DEM pixels [8]. The simulation is over 6 Mars years with 30 min. time steps. White contours indicate the threshold for the stability of subsurface ice.