A MULTI-LAYER SOIL TEMPERATURE MODEL FOR MM5

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1. INTRODUCTION

Currently MM5 predicts ground temperature by the force-restore method (Blackadar 1976, Deardorff 1978) where the ground is divided into two layers. The top slab is considered to be a depth with the vertical scale of the diurnal temperature wave, and the substrate is considered to remain at a diurnal mean fixed temperature. The energy budget, made up of sensible, latent and radiative heat fluxes, forces the top slab temperature to vary depending upon its effective depth and heat capacity, while a relaxation term with a time scale of about (1 day/2 π) acts to restore the temperature to the substrate mean and represents a substrate heat flux. The effective depth and heat capacity can be chosen such that, given a sinusoidal forcing with a period of a day, the top slab temperature variation mimics a multi-layer soil model, giving an accurate energy budget at low computational cost. Blackadar further refined the constants to allow for higher harmonics in the diurnal forcing.

While this approach is certainly adequate for most mesoscale modeling studies, it is becoming apparent, particularly from verifications against surface data, that it has some deficiencies. From these comparisons it is quite evident that the model's surface air temperature often does not recover to the previous day's temperatures when a 24-hr forecast is initialized near the daytime maximum in synoptic situations where there is little difference between the days. There are many possible reasons for this. Moisture availability may be too high causing too much latent heat flux at the expense of sensible heat flux resulting in the air not warming enough. The planetary boundary layer scheme may be incorrectly distributing the heat in the surface layers. The shortwave radiation at the ground surface may not be sufficient due to the radiative scheme's treatment of clear-air solar flux. The substrate temperature may be too cold leading to a cooling bias in the ground slab temperature. These latter two effects would first affect the ground temperature then the low-level air temperature in the model.

Even though all of these could contribute, study of the real-time forecasts being run at NCAR centered on Colorado, did not seem to reveal any of these to consistently account for the day-time temperature deficit. For instance, incorrect moisture availability would show up as a moist bias in addition to a cool bias. Shortwave radiation was tuned to agree with FIFE's observed fluxes by reducing solar scattering from its default value in MM5 version 1, but the cool day-time bias persisted despite the apparently sufficient solar energy supply. It has been further noticed that there is not only an amplitude deficiency but also a phase lag in modeled versus observed surface air temperature.

These results and observations led us to a re-examination of the assumptions behind the force-restore method. It can be seen that there are two primary assumptions that need to be questioned if one is interested in accurately treating ground and surface-layer temperature. The first is that the constants used in the slab model are tuned to give the best results when there is a regular diurnal cycle in heating with a period of 24 hours. This alone would lead to a deficiency in the response to faster changes such as cold frontal passages, or a rapid morning rise in solar heating. This is further compounded by the second deficiency which is to assume that the heating is immediately uniformly distributed through the slab.

In reality when a conductive medium, such as the soil, is subjected to a time-varying heating at one end, a decaying wave propagates into the medium, so that deep in the medium the wave is of much smaller amplitude and significantly delayed compared to at the surface. For typical soil the e-folding depth of this decay for a diurnal forcing period is of order 10 cm, and the diurnal wave propagates down at 3 cm/hour. Compared to, for instance, the top centimeter, the 20-cm mean temperature, which represents the ground temperature in the force-restore method, is therefore time-lagged and has a smaller diurnal amplitude. However, in reality the overlying air responds only to the top thin layer, not the mean slab temperature, so correct representation of fluxes would seem to require higher vertical resolution of the soil temperature profile. Moreover the top thin layer of the soil can respond on much shorter time scales to changes in the forcing.

2. THE MULTI-LAYER SOIL TEMPERATURE MODEL

This model provides an improvement in the treatment of ground temperature at minimal computational cost, either in CPU time or memory. In principal any number of levels and thicknesses could be specified, but as implemented the model uses five layers with thicknesses from top to bottom of 1, 2, 4, 8 and 16 cm. Below the bottom level, at 31 cm, the substrate temperature is kept constant in a layer that is 32 cm thick. This model has been compared with a 100-layer 1-cm resolution model and gives closely agreeing results in a one-dimensional test.

The transfer of heat follows the one-dimensional simple diffusion equation as the heat flux, F [W m^{-2}] is linearly proportional to the temperature gradient. Thus,

$$F = -K\rho_s c_s \frac{\partial T_s}{\partial z}, \qquad (1)$$

where K is the soil's thermal diffusivity [m^2 s^{-1}], ρ_s is its density [kg m^{-3}], and c_s is its specific heat capacity [J kg^{-1} K^{-1}]. The flux convergence is proportional to heating. Thus,

$$\frac{\partial T_s}{\partial t} = -\frac{1}{\rho_s c_s}\frac{\partial F}{\partial z}. \qquad (2)$$

This is applied as follows. First (1) is used to determine $F(z)$ within the soil, then (2) can be used given that $F(z=0)$ is known at the surface where it represents the net sensible, latent and radiative flux.

3. PRACTICAL CONSIDERATIONS

To apply this method within the framework of MM5, there are a few details to consider. Firstly, it appears that the soil model requires both soil diffusivity and soil heat capacity to run it, while the slab model requires only one soil-dependent constant, thermal inertia (χ [J m^{-2} K^{-1} s$^{-\frac{1}{2}}$]). However, there is a relation that

$$\chi = \rho_s c_s K^{\frac{1}{2}}.$$

and furthermore the temperature variation at the soil surface only depends on χ. This allows us to use the existing thermal inertia specified as a function of land-use for MM5 as long as we fix either $\rho_s c_s$ or K, since we are only interested in the temperature behavior at the surface. K is chosen to be fixed at some intermediate value between sand and clay soils ($= 5 \times 10^{-7}$ m^2 s^{-1}) and this fixes the timestep that can be used for numerical stability. The stability criterion is that

$$1 \; > \; 2\frac{K\Delta t_{soil}}{\Delta z^2}, \qquad (3)$$

giving a timestep limit of 100 s in the case of 1-cm layers, and sub-time-steps are carried out in each ground temperature column if needed to ensure this criterion is met.

With diffusivity fixed, all the thermal inertia's variation is in the heat capacity as in Blackadar's method (which is equivalent to scaling the depth of the soil model according to soil type).

Another practical consideration, when using this multi-layer model is how to initialize the temperature profile within the soil since no information exists. Use is made here of the model's ground temperature and substrate temperature at the initial time as these are readily available from the MM5 preprocessing system. The simplest approach is to apply a temperature profile that varies linearly with depth between the ground temperature at $z = 1$ cm and the substrate temperature, centered at a depth of 47 cm. This profile was chosen as it represents a steady solution to the diffusion equation, so that the only initial tendency is in the top layer. However in reality the profile would depend on the last day's history of ground temperatures, and it is not clear to what extent this assumption affects the soil model's behavior.

This scheme is still being evaluated and will be released as an option in MM5 version 2. A full set of multi-layer prognostic equations would include a moisture budget, but adding this has to allow for complexities associated with vegetation, soil moisture initialization and run-off.

4. REFERENCES

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