Prediction of Soil Temperatures of a Soil Mulched with Transparent Polyethylene

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ABSTRACT

A numerical model for the prediction of mulched soil temperature has been developed. The model takes into consideration environmental condition as well as physical characteristics of both the mulch material and the soil. The ability of the model to predict the temperature of the mulched and unmulched soil is tested.

It is shown that soil temperatures of a wet mulched soil are significantly increased, primarily due to the elimination of evaporation and partly due to the greenhouse effect of the polyethylene film. In the case of a dry mulched soil the greenhouse effect is dominant. Thus a smaller temperature increase is obtained.

1. Introduction

Soil mulching with transparent polyethylene is widely used to increase soil temperatures. Courter and Debker (1964), Takatori *et al.* (1964), Hopen (1965), Vandenberg and Tiessen (1972) and many others have shown that soil mulching increases yields, promotes earlier maturing of certain vegetables and controls weeds.

Katan *et al.* (1976) have shown that during the hot summer season in Israel, polyethylene mulching of irrigated soils prior to planting can be used for the control of diseases caused by soilborne pathogens. Their results indicate that populations of various kinds of fungi pathogentic to plant crops were eliminated or markedly reduced up to the depth of 25 cm after a period of two weeks, resulting in a significant decrease in incidence of various plant diseases. They indicated that a maximum temperature increase of ~10°C in the upper layer (5 cm depth) was sufficient for this task. The use of polyethylene mulching to increase soil temperature in order to control disease is superior to other methods such as fumigation or use of pesticides, since it does not involve phytotoxicity or pesticides residues, and is also more economical.

In this paper a one-dimensional planetary boundary-layer (PBL) model described in detail in Pielke and Mahrer (1975) and in Mahrer and Pielke (1977) is used to predict soil temperatures of a mulched and unmulched soil. The primary goal of the numerical model is to use it instead of a network of observation to provide soil temperatures of a mulched soil under different climatic conditions.

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2. The model

Because details of the model have been reported by Pielke and Mahrer (1975) and Mahrer and Pielke (1977), only a brief description of the model will be given here.

a. Boundary layer

The surface layer fluxes of heat, moisture and momentum are based on the work of Businger (1973), while the turbulent mixing in the remainder of the PBL was parameterized using an exchange coefficient formulation as described by O'Brien (1970). The depth of the PBL is predicted utilizing a formulation introduced by Deardorff (1974) and tested in Pielke and Mahrer (1975).

b. Ground surface

The temperature at the soil-air interface is calculated using an energy budget where the long- and shortwave radiation, the soil heat flux and the turbulent mixing of sensible and latent heat are considered.

The energy balance equation is given by

$$(1-\alpha)R_s+R_L+H+E-S-\sigma T_s^4=0, \qquad (1)$$

where α is the albedo, R_s the incoming solar radiation, R_L the incoming longwave radiation, and H, E and S are the sensible, latent and soil heat fluxes, respectively.

The specific humidity at the soil air interface, which is used in the evaluation of the latent heat flux, is given by

$$q_0=S_w q_s(T_s)+(1-S_w)q, \qquad (2)$$

where S_w is the soil wetness, $q_s(T_s)$ is the saturated specific humidity at the soil temperature T_s, and q is the specific humidity of the air at the first layer of the model. The following obvious restriction was used:

$$q_0 \leqslant q_s(T_s).$$

c. *Radiation*

The changes of air temperature due to short- and longwave radiative fluxes are parameterized following the methods of Atwater and Brown (1974). Heating of the atmosphere by shortwave radiation is confined to water vapor, while carbon dioxide and water vapor are considered in the longwave radiation heating/cooling algorithm. Mahrer and Pielke (1976, 1977) discuss the surface heat budget and radiative heating routines in detail.

d. *Numerical scheme*

The vertical diffusion terms are represented by the method discussed in Paegle *et al.* (1976) which was shown to be extremely accurate even for long time steps.

e. *Boundary and initial conditions*

At the initial time, the temperature and specific humidity profiles are specified while the velocity profile is determined through an Ekmanlayer type balance equation in the PBL (see Mahrer and Pielke, 1976, p. 1394) and is specified in terms of the geostrophic shear above that layer.

f. *Soil layer*

For the soil layer we solve the equation

$$\frac{\partial T_s}{\partial t}=\frac{\partial}{\partial z}\left(K_s\frac{\partial T_s}{\partial z}\right), \tag{3}$$

where K_s is the soil heat diffusivity, assumed constant with depth in all the experiments.

g. *The mulched soil*

When considering the mulched soil it was assumed that 1) no evaporation takes place; 2) air temperature, relative humidity and wind speed are unaffected by the mulched soil; 3) short- and longwave radiative fluxes are modified by the cover according to its transmissivity, reflectivity and absorptivity properties; and 4) the air gap between the polyethylene film and the soil is small enough to neglect heat exchanges due to condensation or evaporation processes.

In order to evaluate the surface and polyethylene temperatures, two simultaneous energy balance equations must be written for the soil and for the cover.

For the soil we have (with soil emissivity = 1)

$$t_s(1-\alpha)R_s+t_lR_l+\epsilon\sigma T_p{}^4-\sigma T_s{}^4+H_0-S=0, \tag{4}$$

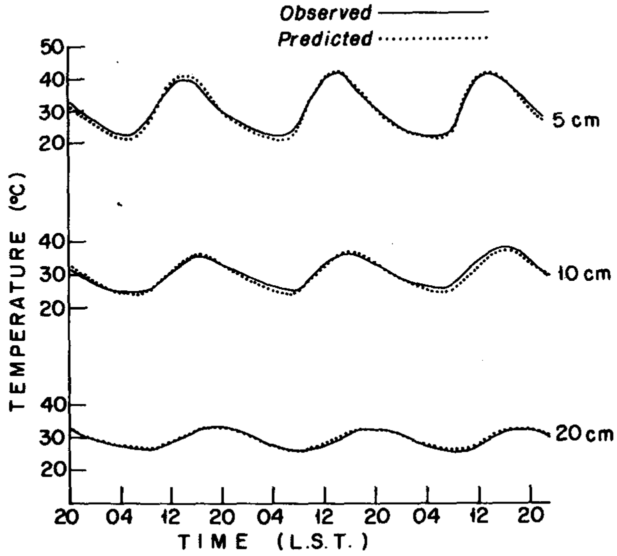

FIG. 1. Observed and predicted temperatures of unmulched dry soil at depths of 5, 10 and 20 cm as a function of time (Experiment 1).

where t_s and t_l are the polyethylene transmissivity values for short- and longwave radiation, respectively, T_p is the polyethylene temperature, ϵ is the emissivity of the polyethylene ($\epsilon=1-t_l$ was used in this study) and H_0 is the sensible heat flux expressed following Kimball (1973) by $H_0=0.4\rho C_p(T_s-T_p)^{4/3}$, with ρ being the air density and C_p the specific heat of air.

For the polyethylene, we obtain

$$\delta R_s+\epsilon R_l+\epsilon\sigma T_s{}^4+H-H_0-2\epsilon\sigma T_p{}^4=0. \tag{5}$$

Here δ is the polyethylene absorption coefficient for solar radiation ($\delta=0$ was used in this study) and H the sensible heat flux to the air.

Eqs. (4) and (5) are solved simultaneously for T_s and T_p. The resulting soil temperature at every time step is used as a top boundary condition in Eq. (3).

3. Results

Two observational and numerical experiments were performed in order to verify the model results: 1) dry sandy soil (moisture content 5%), 2) wet sandy soil (moisture content 15%). In these experiments a 0.04 mm transparent polyethylene film was used. Its transmissivity was 88% in the short wave spectrum and 70% in the infrared spectrum.

Soil temperatures of the mulched and unmulched soil at depths of 5, 10 and 20 cm were measured every hour, using a Grant model D miniature temperature recorder.

a. *Experiment 1* (*dry soil*)

The observations were taken in the experimental area at the Faculty of Agriculture in Rehovot, Israel, during the month of May 1978. The results of the numerical model were tested for several days during the time of the observations and since they showed a similar pattern, only a verification of a typical period during 15–17 May 1978 is presented.

The model was initiallized using the Bet Dagan 2000 LST 15 May 1978 radiosonde ascent, while the vertical distribution of the initial soil temperatures was obtained from the local observations.

The surface albedo, soil conductivity, density and heat capacity were 0.20, 0.003 cm² s⁻¹, 1.55 g cm⁻³ and 0.32 cal g⁻¹ °C⁻¹, respectively. These soil characteristics corresponded to a sandy, dry soil with a wetness content of ~5%.

Figs. 1 and 2 show the observed and predicted soil temperatures at depths of 5, 10 and 20 cm in the mulched and unmulched soils. As seen from the figures, good agreement between the observed and the predicted values is obtained.

In order to study the soil temperature forecast more quantitatively, an error analysis for four 3-day periods was performed. The magnitude of the errors in the temperatures was estimated from

$$E=\bar{T}^{-1}\sum_{t=1}^{\bar{T}}|T_t^o-T_t^p|,$$

where $\bar{T}$ is the total time in hours, and T_t^p and T_t^o are the predicted and observed soil temperatures, respectively.

The results of this error analysis for the depths of 5, 10 and 20 cm showed that the average error in all cases was at the range of 0.7–1.3°C.

Following one of the reviewers suggestions, an examination of the mean error for daytime and nighttime periods was performed; however, no specific trends of the errors were detected.

Fig. 3 shows the observed soil temperatures at the depths of 5, 10 and 20 cm in the mulched and unmulched dry soils. The predicted results are not shown here since they showed almost the same pattern (Figs. 1 and 2).

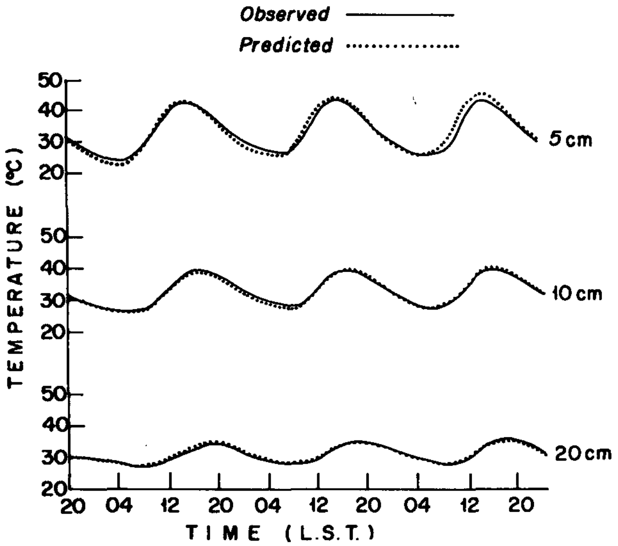

FIG. 2. As in Fig. 1 except for the mulched soil.

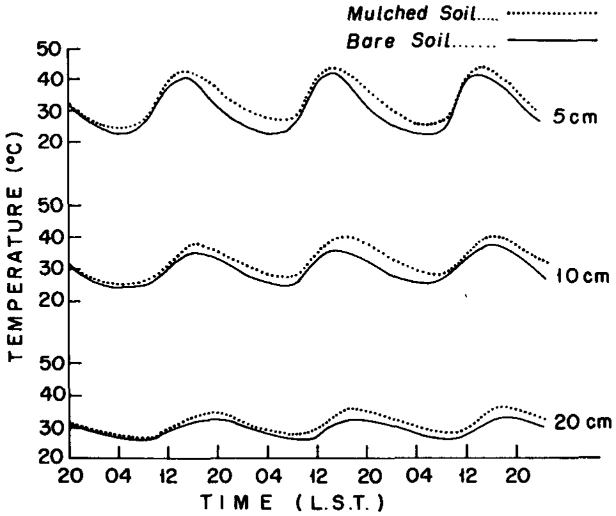

FIG. 3. The observed mulched and unmulched temperatures of dry soil at depths of 5, 10 and 20 cm as a function of time (Experiment 1).

Only a small temperature increase in the mulched soil relative to the unmulched soil is depicted, amounting to a maximum of 4°C at the 5 cm level; it is mainly due to the greenhouse effect of the cover. This temperature increase is smallest during the early morning hours and is probably due to the reduction of the incoming solar radiation by the polyethylene film at times when marked soil heating takes place. On the other hand, considerably higher mulched soil temperatures are found during the late afternoon and night hours when intensive cooling takes place and the polyethylene film reduces the heat losses by longwave radiation.

b. *Experiment 2* (*wet soil*)

Experiment 2 was performed for a wet soil with a water content of 15% during the month of June 1978. As in experiment 1 several days were tested, typical results for which are provided below for the period between the 15th and the 17th. The values of soil albedo, conductivity, density and heat capacity were 0.20, 0.01 cm² s⁻¹, 1.63 g cm⁻³ and 0.42 cal g⁻¹ °C⁻¹.

Figs. 4 and 5 show the observed and predicted soil temperatures of the mulched and unmulched soils, respectively. As depicted in the figures the agreement between the observed and predicted values is good. The results of an error analysis (described in the dry soil experiment) are in the range of 0.6–1.2°C.

In this experiment, the effect of mulching is much more pronounced and the average increase of the mulched soil temperature is as large as 9°C at a depth of 5 cm (Fig. 6), in comparison to an average temperature increase of 3°C in the dry soil case (Fig. 3). This result suggests that in a wet soil the primary effect of

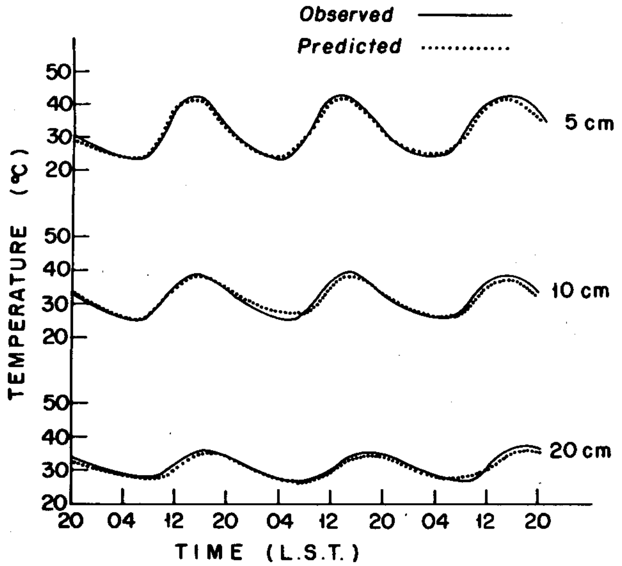

FIG. 4. Observed and predicted temperatures of wet unmulched soil at depths of 5, 10 and 20 cm as a function of time (Experiment 2).

the transparent polyethylene during the daytime is to eliminate evaporation, and thereby increase the amount of heat available for soil heating. The greenhouse effect, which is the main heating process in a dry soil, contributes a relative small part (20%) in this case.

A noticeable feature in both the observed and predicted results is the buildup time for the high temperatures after the mulch is applied. This buildup time takes ~24–36 h depending on the depth. For instance, in Fig. 6 the lowest and the highest mulched soil temperatures at a depth of 5 cm in the first day are 27 and 45°C, while in the second day they are 31.5 and 49°C.

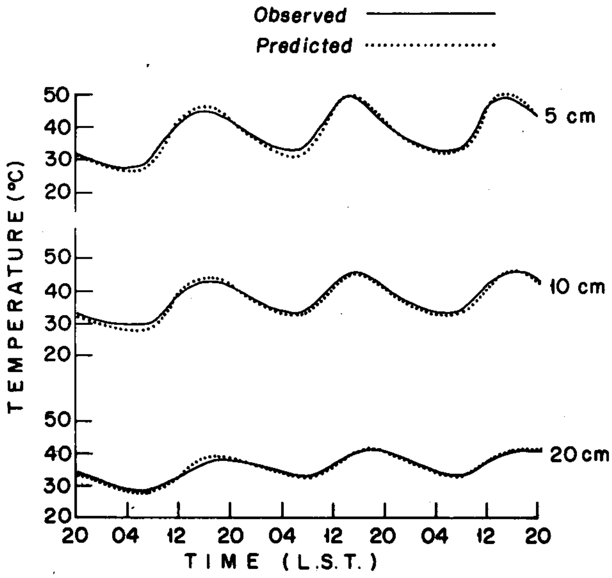

FIG. 5. As in Fig. 4 except for the mulched soil (Experiment 2).

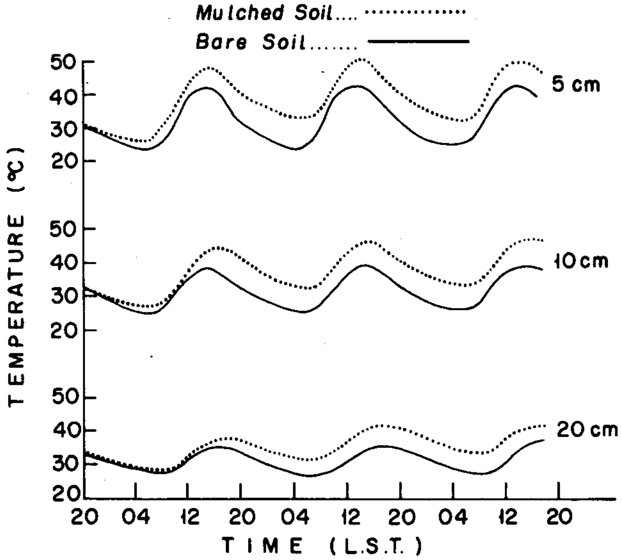

FIG. 6. Observed temperatures of wet mulched and unmulched soil at depths of 5, 10 and 20 cm as a function of time (Experiment 2).

4. Conclusion

The ability of the numerical model described in this paper to predict the temperatures of a mulched and unmulched soil has been tested and verified. A model of this kind can be used in lieu of an expensive network of observations to predict the soil temperature regime under different meteorological conditions, and for various types of plastic materials. Using this information, one can evaluate the most appropriate time for mulching with respect to particular agriculture and plant requirements. Information of this kind can be used in agriculture planning, such as prediction of the earliest possible date for sowing with and without mulching, and prediction of the most effective dates (with respect to agriculture needs and maximum temperatures required) for mulching to control diseases caused by soilborne pathogens (Katan *et al.*, 1976).

It has been shown that the primary effect of the transparent polyethylene is to eliminate the heat losses by evaporation during daytime and thereby increase the sensible soil heating. The polyethylene film also reduces heat losses by preventing part of the longwave radiation from leaving the ground.

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