NASA-CR-196008

IN-46-CR
12609
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A Model of the CO_2 Exchanges Between Biosphere and Atmosphere in the Tundra

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(NASA-CR-196008) A MODEL OF THE CO2 EXCHANGES BETWEEN BIOSPHERE AND ATMOSPHERE IN THE TUNDRA Final Technical Report, 1 Sep. 1991 - 31 Aug. 1992 (California Univ.) 9 p

N94-35389

Unclas

G3/46 0012609

Final Technical Report
NASA Grant #NAGW-2737
9/1/91 - 8/31/92

1- INTRODUCTION:

The Arctic tundra and boreal forest are critical ecosystems with respect to climate change. On one hand, climate models indicate that warming induced by the greenhouse effect will be larger in polar regions, and on the other hand, these ecosystems contain large amounts of buried, partially decomposed organic carbon. These considerations raise the question of a possibly large biotic feedback to climate change in the northern ecosystems.

Northern ecosystems are characterized by very low temperature and the presence of permafrost (permanently frozen ground) impeding soil drainage, creating high soil moisture. This in turn inhibits the development of large micobiotic communities and hinders decomposition. As oxygen decrease in this very wet environment, oxidation is replaced by anaerobic decomposition leading to the formation of methane and CO_2.

Climate change could affect the net soil carbon balance in two ways: (1) changes in mean daily temperature, precipitation and cloudiness, (2) changes in surface conditions. Since the amount of CO_2 in the northern soils is very large, a small change in their decomposition rate would have a significant impact on northern ecosystems carbon balance. To predict the response of the ecosystem to climate change, it is very important to first be able to predict the response of permafrost, soil temperature and soil moisture to climate change. The physical model described next will provide an estimate of the impact of climate change on permafrost and on the soil temperature and moisture regimes.

2- THE MODEL:

In order for the model to be applied easily to different sites, the input parameters and variables are restricted to readily available climatic data and to a few site parameters (Table 1). To estimate the response of the system to climatic conditions which differ from present conditions, it is essential to avoid the use of empirical laws to describe the relationships between a variable of interest (e.g., the thaw depth) and variables which influence the latter (e.g., air temperature, growing season length). Indeed, large data sets are required to develop and test regression laws and this restricts the generality of the models based on such laws. In particular, since regression laws are based on measurements made under current climatic conditions, these models may not be valid under different climatic conditions. Consequently, a deterministic model has been developed which explicitly parameterizes the physical processes that determine the soil temperature and moisture regime (e.g., heat conduction in the ground and energy transfer at the surface). Additionally, it is not logistically feasible to use daily or monthly soil moisture contents as input to a model because of the lack of uniform data sets (soil moisture is particularly difficult to measure and its value is very sensitive to the measurement technique). Therefore, in the present model, the soil moisture content is calculated at each time step, based on water budgets in each soil layer. Finally, computed soil moisture contents are used to reevaluate daily the thermal coefficients. The general structure of the model is portrayed in Fig. 1.

3- VALIDATION:

Partial computed and observed snow depth of the 1970-71 snow cover at Barrow, Alaska are shown in Fig. 2. In this simulation, precipitation monthly means were replaced by monthly values from 1970-1971. The agreement between the model's results and the observations is quite good. In particular, the length of the growing season, which plays a very important role in terms of $C0_2$ exchanges, is correctly predicted by the model. A comparison between observed mean, maximum and minimum solar radiation and net radiation over the coastal tundra at Barrow, and computed radiation levels is shown in Fig.

3. One can see that the computed values are comprised in the range of observed radiation values. For soil temperature, a numerical method used to solve the heat conduction equation was first checked by comparing the results of the model with an analytical solution. The numerical scheme is implemented, using a time step of 0.25 day. The step change in surface temperature leads to freezing from the surface downward. After a rapid initial frost penetration, the rate of frost penetration decreases with time, as predicted by the analytical solution (i.e., the depth to the freezing front is proportional to the square root of time). As seen in Fig. 4, the frost penetration after 50 days is very robust with respect to changes of T. However, if ΔT is too small, the temperature could leap across the interval where heat is released or absorbed, without latent heat showing up in the effective heat capacity because the temperature never actually fell in that narrow range.

Figure 5 shows the observed and computed daily mean temperatures at various depths. Except for the surface temperature at the beginning of October, the computed results closely reproduce the observed values during the entire observation period. This discrepancy may be related to extreme values in the surface conditions which were smoothed out by using monthly averaged input data.

Figure 6 shows the effect of the snow cover on the soil temperature annual cycle at various depths. The results in the presence of snow have been compared with measurements during snow-melt in 1971. The model very accurately simulates the increase in soil temperature near the surface as the snow melts. It is interesting to compare the depth of the active layer in absence and in presence of snow: the active layer is about 6 cm deeper in absence of snow than in the presence of snow of accumulated depth of 40 cm.

4- SENSITIVITY ANALYSIS:

A simple sensitivity analysis was carried out to assess the response of the model to changes in a number of important input variables and parameters. Air temperature, solar radiation, precipitation, and parameters such as the organic layer thickness and the soil thermal properties were altered by plus or minus a given percentage. Results of these simulations were compared to values from the ambient standard simulations for Barrow.

The sensitivity of the responding variables to changes in climatic and soil variables was calculated by subtracting the value for each responding variable from the value for the standard case and then dividing by the standard case value. The standard case corresponds to the simulations outlined in the foregoing, in the presence of snow:

1. Sensitivity to soil thermal coefficients and soil moisture content.
    a -Constant thermal coefficients
    b -Moisture-dependent coefficients
2. Sensitivity to climatic variables
    a -Incoming solar irradiance was varied by Δ20%.
    b -Precipitation was changed by Δ50%.
3. Sensitivity to the organic layer thickness
4. Sensitivity to aerodynamic and vegetation resistances

For details on the this analysis refer to Waelbroeck, C. (1993).

5- SIMULATION OF A 8'C AIR TEMPERATURE INCREASE OVER 100 YEARS:

The model was first run for 20 years with standard inputs in order to reach a near-equilibrium solution. Then, air temperature was increased at a rate of 0.08'C per year. Figure 7 shows the evolution of the annual maximum thaw depth and mean soil moisture content. Zero on the abscissa corresponds to the time when air temperature begins its increase.

Not surprisingly, the evolution of the maximum thaw depth does not mimic the linear increase in air temperature. As the maximum thaw depth first increases in response to warmer air temperatures, drainage conditions improve and mineral soil water content decreases in the subsequent year. This results in a deepening of the active layer, which adds up to the deepening due to the air temperature increase. In short, the rate at which the permafrost table lowers, increases with time because of the positive feedback due to the dependence of mineral soil moisture on the depth to permafrost.

The precise time at which this change in maximum thaw depth progression takes place, clearly depends on the choice of the parameters used in the model. For instance, the transition between permafrost-dependent drainage conditions and good drainage conditions is probably less abrupt in reality than represented here. Nevertheless, it can be speculated that passage from one type of drainage condition to another would take place in any permafrost terrain subjected to air temperature increases, all other factors remaining constant.

In contrast to mineral soil moisture, organic soil moisture remains very high during the first 21 years or so after the onset of the temperature increase and then decreases steadily. This can be explained by two facts. First, as mentioned earlier, the organic layer resembles a sponge and its water content can be assumed to be independent of drainage conditions. Secondly, although evapotranspiration increases, organic soil moisture content remains high because the maximum rooting depth increases with increasing depth of the active layer, so that the relative amount of water lost from the organic layer through transpiration decreases.

In conclusion, three phases can be distinguished in the response of soil temperature and hydrology to an increase in air temperature (m(1) indicates moisture content in % of dry weight, for layer 1):

-phase 1: m(l) remains high whereas soil temperature increases, leading to enhanced organic matter decomposition.

-phase 2: m(l) decreases while the rate of change of soil temperature continues to increase faster. During this phase soil decomposition response cannot be predicted a priori and will depend on whether soil moisture is above or below the optimal water content.

-phase 3: m(l) decreases and soil temperatures increase at rates much slower than during phase 2 and in a quasi-linear fashion. Therefore, the rate of change of soil decomposition should be much slower than during phase 2.

6- SUMMARY AND CONCLUSIONS:

A physical model of the soil thermal regime in a permafrost terrain has been developed and validated with soil temperature measurements at Barrow, Alaska. The model calculates daily soil temperatures as a function of depth and average moisture contents of the organic and mineral layers, using a set of 5 climatic variables (i.e., air temperature, precipitation, cloudiness, wind speed and relative humidity).

The model is not only designed to study the impact of climate change on the soil temperature and moisture regime, but also to provide the input to a decomposition and Net Primary Production model. In this context, it is well known that $C0_2$ exchanges between the terrestrial biosphere and the atmosphere are driven by soil temperature through decomposition of soil organic matter and root respiration. However, in tundra ecosystems, net $C0_2$ exchange is extremely sensitive to soil moisture content, therefore it is necessary to predict variations in soil moisture, in order to assess the impact of climate change on carbon fluxes. To this end, the present model includes the representation of the soil moisture response to changes in climatic conditions.

The results presented in the foregoing demonstrate that large errors in soil temperature and permafrost depth estimates arise from neglecting the dependence of the soil thermal regime on soil moisture contents. Permafrost terrain is an example of a situation where soil moisture and temperature are particularly interrelated:

(i) drainage conditions improve when the depth to the permafrost increases,

(ii) a decrease in soil moisture content leads to a decrease in the latent heat required for the phase transition so that the heat penetrates faster and deeper, and the maximum depth of thaw increases,

(iii) as excepted, soil thermal coefficients increase with moisture.

Factors (i), (ii) and (iii) are represented in the model. Factor (ii) refers to the physics of heat transfer in a multi-layer medium with phase change and is treated exactly in this model, within the limitations imposed by the spatial resolution of the numerical scheme (depth increment of 5 cm). Conversely, the parameterization of (i) and (iii) is empirical. Therefore, one should bare in mind that the simulations presented here are not intended to provide accurate estimates of the variables magnitude, but rather to indicate the trend the variables will follow in response to changes in climatic conditions or soil parameters (see sensitivity analysis, section 4). In particular, the response of the soil thermal regime to variations in soil moisture content is radically different whether (iii) is taken into consideration or not: whereas a decrease in soil moisture content of both the organic and mineral layer leads to a deeper active layer when the moisture dependence of the thermal coefficients is neglected, the present study shows that a decrease in the organic layer moisture content actually induces a significant decrease in the organic soil thermal conductivity and hence, a decrease in maximum thaw depth.

7- REFERENCE:

Waelbroeck, C., 1993. Climate-Soil Processes in the Presence of Permafrost: A System Modelling Approach. *Ecological Modeling*, **69**, pp.185-225.

8- PATENTS, INVENTIONS AND PROPERTY

For the period of this award, there are no patents, inventions or property to report.

TABLE 1

Input variables and parameters

(A) Climatic data	
Mean daily or monthly:	air temperature (°C) water equivalent of total precipitation (cm) cloudiness (tenths of sky covered) wind speed (m s^{-1}) relative humidity (%)
Annual maximum depth of the snow cover (cm)	
(B) Soil and site parameters	
Latitude, longitude and elevation	
Aspect, percent of slope	
Thickness of the organic layer (cm)	
Mineral soil texture (fine grained, coarse)	
Organic and mineral soil:	bulk density (kg m^{-3}) volumetric moisture capacity (kg m^{-3}) thermal coefficients
Mean leaf stomatal resistance of the vegetation (s m^{-1})	

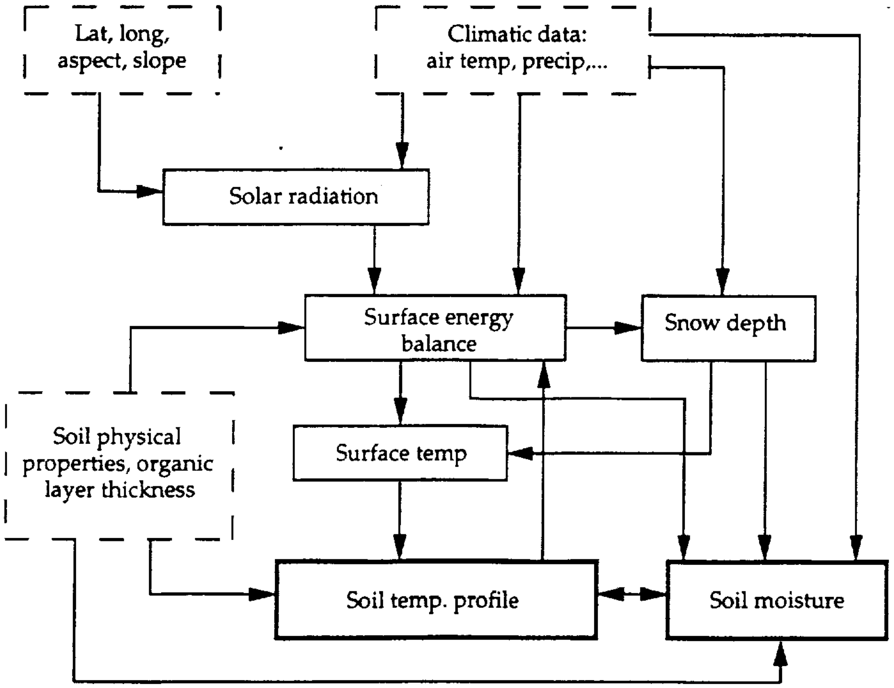

Fig. 1. Diagram of the various factors influencing the soil temperature profile and the soil moisture regime. Dashed boxes indicate input variables and site parameters.

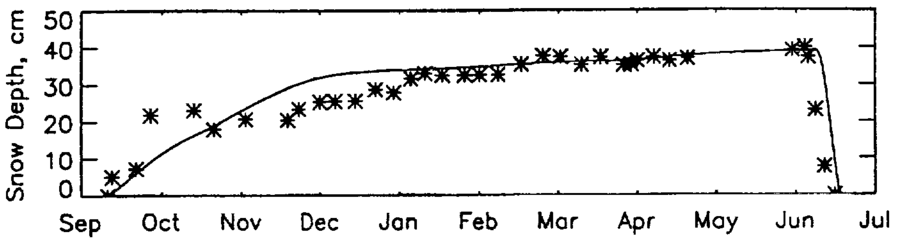

Fig. 2. Computed (———) and observed (*) snow depth of the 1970–71 snow cover at Barrow.

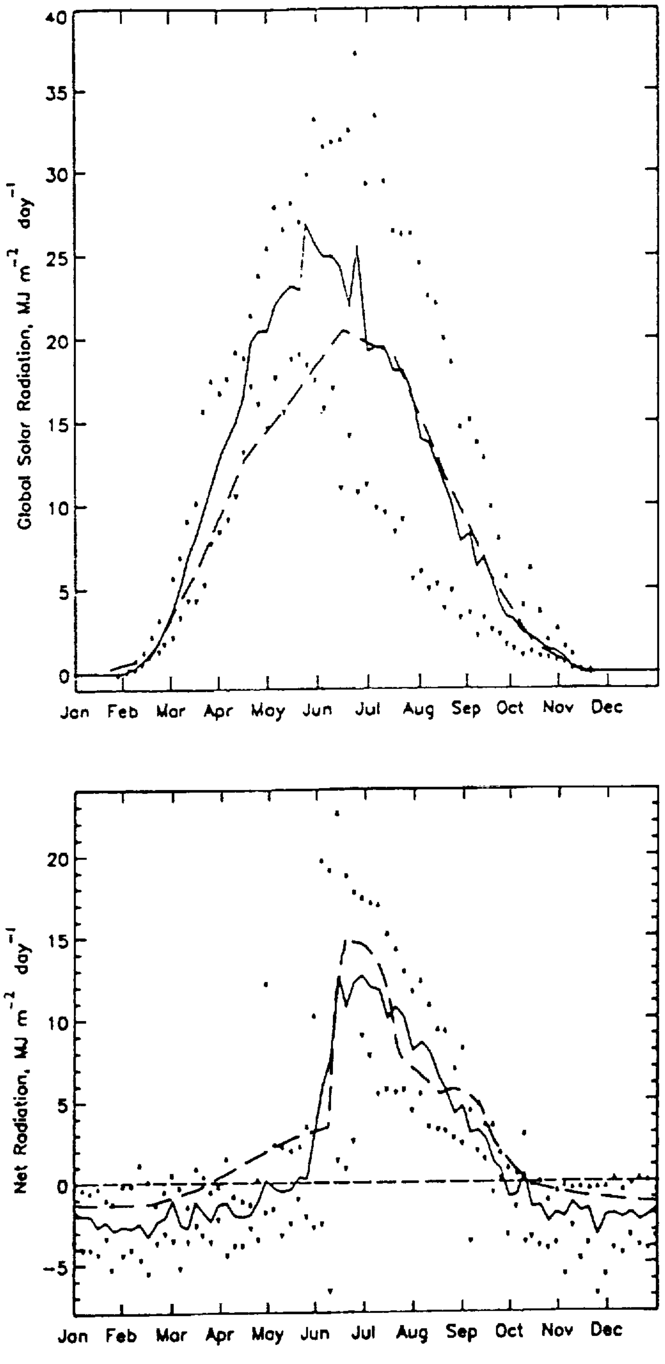

Fig. 3. Computed (— — —) and observed mean (———), maximum (▲) and minimum (▼) global solar radiation and net radiation over the coastal tundra at Barrow.

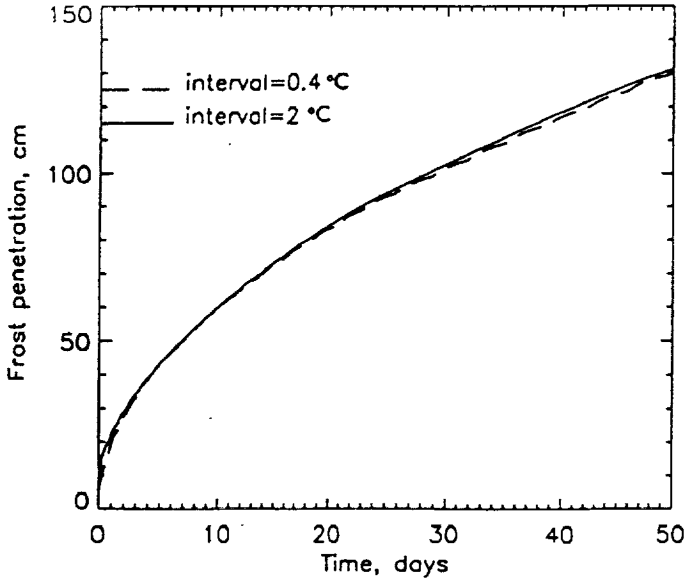

Fig. 4. Frost penetration as a function of time; numerical solution of the Neumann freezing problem.

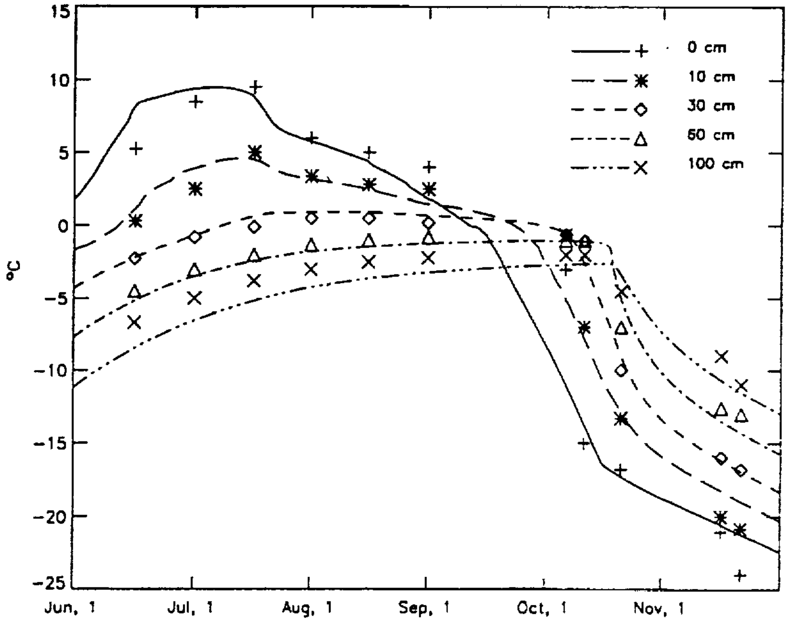

Fig. 5. Computed (———, — — —, – – –, – · – · –, – · · · –) and observed (+, *, ◇, △, ×) temperatures at various depths.

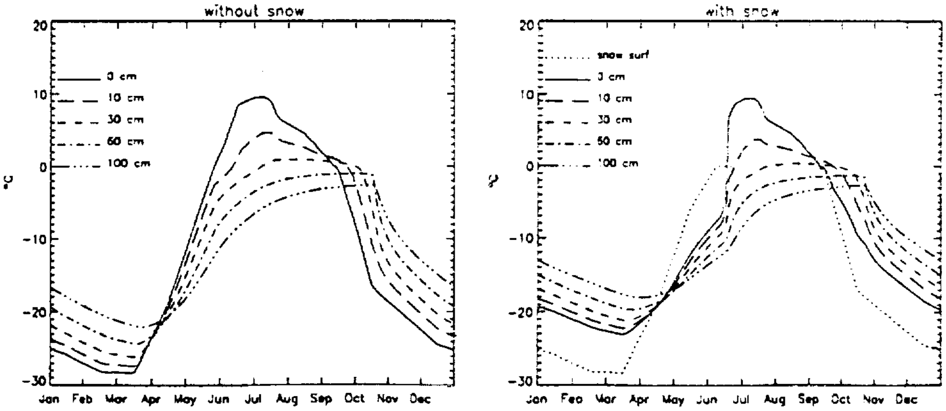

Fig. 6. Illustration of the effect of the snow cover on the soil thermal regime.

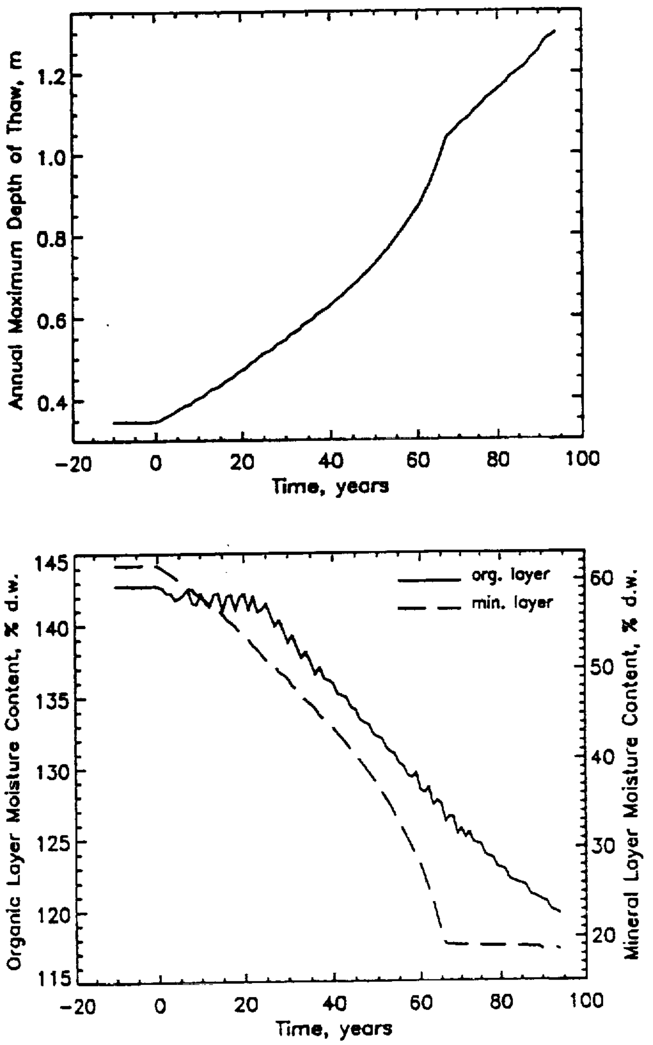

Fig. 7. Evolution of the depth to the permafrost and of the moisture content of both layers in response to a constant increase in air temperature of 0.08°C/year.