A Mechanism for the Influence of Vegetation on the Response of the Diurnal Temperature Range to a Changing Climate

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ABSTRACT

Observations over the last century reveal that the mean air temperature over land has increased by 0.5 K or more while the mean diurnal temperature range (DTR) has decreased. Several mechanisms have been proposed to account for this phenomenon and here we suggest another potential factor, the physiological behavior of vegetation in response to climate. We analyze the influence of vegetation on the response of the DTR to perturbations in the state of the climate and vegetation, using a physiologically based landsurface model. Increasing downwelling longwave radiation and surface air temperature together, conditions that could occur as a result of doubling of atmospheric CO_2, produced little change in the DTR. Changes in the state of the vegetation (i.e. amount, physiological capacity, stress) produce changes in the DTR of the order or larger than observed. Results show that climate modeling studies of the DTR changes need to incorporate the response of vegetation and suggest that recently reported increases in vegetation over the last decade could contribute to the observed decrease in the DTR.

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I Introduction

There is a general consensus that the global mean surface air temperature has increased by about 0.3 to 0.6 K in the last half of this century, in parallel with a 5 Pa increase in the atmospheric partial pressure of CO_2 (e.g. Bolin et al. 1995). Karl and colleagues (e.g. Karl et al. 1984; Easterling et al. 1997) reported that during the period 1951 to 1993, the diurnal temperature range (*DTR*) on land has generally decreased as mean surface temperatures have increased. The decrease in *DTR* is associated with larger increases in nighttime minimum relative to daytime maximum temperatures.

A number of mechanisms have been identified that could cause the *DTR* to decrease as the mean temperatures increase. These include changes in cloud cover, atmospheric water vapor, tropospheric aerosols, atmospheric turbulence, soil moisture and snow cover. Increases in the first three could lead to reductions in the incoming surface short wave radiation during the day, and to increases in the downwelling surface long wave radiation at night. Atmospheric turbulence and soil moisture can affect the heat and water vapor fluxes from the surface, which are generally much larger during the day than at night. Reductions in snow cover resulting from increased mean temperatures would be expected to increase the *DTR*, especially between fall and spring, through a reduction in surface albedo. These mechanisms have been evaluated in several modeling studies (e.g. Cao et al. 1992; Verdecchia et al. 1994; Mearns et al. 1995) . Hansen et al. (1995) examined the role of CO_2, aerosols, and clouds on the *DTR* and mean temperatures, and argued that in climate simulations, forcings that increase the mean temperature generally do not affect the *DTR* to the extent that is observed. However, we are aware of no study that has considered the diurnal physiological responses of vegetation nor the state of the vegetation as they affect the *DTR*.

The highly interactive nature of GCMs as well as weaknesses in their parameterizations make

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it difficult to identify the mechanisms underlying changes in the *DTR*. It is useful, therefore, to isolate the vegetation responses to a climate forcing from the feedbacks that occur in climate models so that the vegetation's contribution to the climate system can be understood. The purpose of this study is to examine how the diurnal temperature cycle of vegetated land surfaces responds to changes in external forcing and the biophysical state of the vegetation. We use the SiB2 land surface model (Sellers et al. 1996a) in an off-line mode with prescribed meteorology for a number of scenarios highlighting the impact of vegetation on *DTR*. Off-line simulations do not account for feedback between the surface fluxes and the driving variables, and as such they allow us to better understand how the vegetation component of the climate system responds to given climate forcing.

II MODEL

a. Land surface Model

SiB2 (Simple Biosphere Model Version 2) land surface model couples energy, momentum, CO_2 and water fluxes in a consistent way for use in GCMs, as a replacement for and an advancement over the "bucket-type" models (see Sellers et al. 1997). SiB2 includes parameterizations of canopy physiological responses (photosynthesis, stomatal conductance) and was designed to utilize satellite measurements for many of the important vegetation boundary conditions such as fraction of short wave radiation absorbed, leaf area index, albedo and roughness.

In our GCM simulations (see Randall et al. 1996) transpiration from vegetated land surfaces generally accounts for up to 60% of the total latent heat flux (E) over the year, the rest coming directly from the soil and from evaporation of precipitation intercepted by the canopy and soil. Physiological control of transpiration arises from the response of canopy conductance to photosynthetically active radiation (*PAR*) absorbed by the canopy, and to environmental conditions. The expression describing canopy conductance in SiB2 is relatively simple, but it is

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based on physiological and ecological principles and is consistent observations (Collatz et al. 1991, Collatz et al. 1992, Sellers et al. 1992):

$$g_c = \frac{m \, h_s \, A(T_c, c_i, PAR, V_m, W)}{c_s} \frac{FPAR}{\bar{\bar{k}}} \quad + \quad b(W) \, LAI, \qquad (1)$$

where A is leaf net photosynthesis, which is a function of the physiological interactions with canopy temperature (T_c), leaf internal CO_2 partial pressure (c_i), absorbed solar PAR, nutrition (V_m), and soil water stress (W); h_s and c_s are the surface relative humidity and CO_2 partial pressure respectively; m is a parameter expressing the overall sensitivity of g_c to the rest of variables in this term of the equation and b is the minimum stomatal conductance approached when photosynthesis is not active, e.g. at night and during dormant periods. $FPAR$ is the fraction of incident PAR that is absorbed by the green, k is the mean light extinction coefficient of the canopy (see Sellers et al. 1992), and LAI is the green leaf area index. The parameters m, b and V_m are vegetation type-dependent and time-invariant; in contrast, $FPAR$, k, and LAI vary seasonally, largely independent of vegetation type and $FPAR$ and LAI parameters can be obtained from satellite data. T_c, c_i, h_s, c_s, and W are state variables calculated by the model and must be solved for numerically. Equation (1) illustrates that g_c is highly sensitive to both prescribed parameters and to the state of the climate.

SiB2 has been tested against observations and matches reasonably well with measured fluxes for a number of diverse vegetation types, e.g. forests, grasslands (e.g. Colello et al. 1997, Denning et al., 1996a,b, Rocha et al., 1996). Other landsurface models of this type produce similar energy flux responses to meteorological forcing, as long as soil moisture is not limiting (Koster and Milly, 1997)

III DATA

Observations show northern high latitude regions have generally experienced large decreases (5-3K) in DTR between 1950 and 1993 (Easterling et al. 1997). For this reason we choose for

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our off-line analysis a boreal region in north-central Canada. The meteorological data were obtained from a Black Spruce forest site near Thompson, Manitoba as part of NASA's BOREAS Program.

The input data include shortwave incoming radiation (*SW*), longwave incoming radiation (*LWD*), temperature (T_m) water vapor pressure (e_m), wind speed and precipitation measured above the canopy. A period of 11 rainless days in July were selected. Peak midday *SW* ranged from 450-700 W m^{-2}, T_m ranged from 282 to 302 K, e_m from 0.7 to 2.2 kPa and wind speed from near 0 to 6 m s^{-1}. Soil water was not limiting so water stress did not influence the results. The vegetation parameters used in the control simulations are given in Sellers et al., (1996b) for evergreen needle leaf forest. FPAR values were estimated as the average in July for north-central Canada from satellite measurements (Sellers et al. 1996b) and corresponded to a leaf area index of 2 consistent with the average reported for spruce and pine stands in this region (see Dang et al. 1997).

A number of simulations were run in which we altered the forcing meteorology, model biophysics, or model parameters, in order to investigate the sensitivity of the DTR to the landsurface parameterization. We also include a brief comparison with results from coupled SiB2 – GCM climate simulations.

IV RESULTS AND DISCUSSION

Off-line SiB2 simulations using our standard parameter data set for boreal forests and observed meteorological conditions produced peak   E and H at midday of about 300 W m^{-2} and peak gross photosynthetic rates of about 11 µmol m^{-2} s^{-1} comparable to values reported for forests of Spruce and Pine during the BOREAS study   (Pattey et al. 1997, Jarvis et al. 1997, Joiner et al., 1999).

Mean Temperature versus DTR Change

Hansen et al. (1995) argued that increasing radiative forcing in GCM simulations always

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increases mean temperatures but generally causes weak responses in the *DTR*. They defined a measure of the change in the *DTR* relative to the mean that we apply here:

$$^{n}DTR = \frac{0.5 \; DTR}{\mid T_a \mid}, \qquad (2)$$

In their study they use observed and simulated surface air temperatures, in contrast to our use of the canopy air space temperature (see Sellers et al. 1996a). For the observed increase in mean surface air temperatures of 0.5 K and decrease in the *DTR* of 0.5 the ^{n}DTR equals 0.5. Hansen et al. (1995) argued that the most plausible mechanism for a decrease in the *DTR* under radiatively forced conditions would be an increase in low clouds over land. Further analysis of climate simulations reported by Sellers et al., (1996c), using the CSU GCM, which includes SiB2, revealed similar results; that radiative forcing by itself does not produce a big enough decrease in the *DTR* relative to the mean temperature to match observations (Table I). In Table I we have noted which of the forcings we describe below produced changes in the ^{n}DTR of a magnitude comparable to or larger than observations. The calculations of ^{n}DTR in Table 1 are based on the difference between the scenario simulations and the controls. The sign of ^{n}DTR depends on the direction of the particular perturbation such that a change in the opposite direction will likely produce similar responses in ^{n}DTR but of opposite sign.

We ran a 10-year integration, using the CSU GCM, in which we reduced physiological stresses (water and temperature) which occurred because of incompatibilities between the simulated climate and the prescribed vegetation parameters. This reduction in stress was accomplished by increasing the high temperature stress parameter (Sellers et al. 1996a) and by increasing the resistance to drainage of water out of the lowest soil layer in the model. The result was a reduction in both the annual mean temperature and the *DTR* over land to the extent that there was a large decrease in ^{n}DTR (Table 1.). Correlated with the decreased stress were increases in E, total atmospheric water vapor content, total cloudiness and precipitation. We

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conclude that the landsurface parameterization in GCMs plays a crucial role in the diurnal temperature response, and must be adequately addressed in modeling studies of the *DTR*. Further detailed analysis of off-line simulations allow us to examine the direct response of land surface model to changes in climate forcing and in the parameterization of the vegetation.

Climate Forcing

Three simulations were carried out in which the meteorological driver data were altered to mimic plausible changes in climate associated with a doubling of atmospheric CO_2 partial pressure. In the first case the air temperature above the canopy (T_m) was increased by 3.2 K. In the second case, long wave down-welling radiation (*LWD*) was increased by 23 W m^{-2} and both the T_m and *LWD* modifications were imposed together in the third case. These perturbations to the driver data were selected from results of $2XCO_2$ GCM simulations reported in Sellers et al. (1996c), and were applied at each time step (1/2 hour) for north-central Canadian boreal forest. In these cases the T_m modification also included changing the above canopy water vapor pressure to maintain the relative humidity at the values of observed driver data. Doubling of atmospheric CO_2 can cause stomata to close and, therefore, reduce canopy conductance (Equation (1), Sellers et al. 1996c), but for these runs this response was not invoked. In the next section, variable stomatal responses will be addressed.

The effects of increased T_m and *LWD* were investigated separately and together to identify contributing mechanisms to the overall response. Increasing above canopy air temperatures raises the day time maximum canopy air temperatures (~2.8 K), while the *LWD* forcing had virtually no effect at midday (Figure 1). Day time air temperatures are warmer than the air above, so increasing T_m reduced the temperature gradient resulting in decreased sensible heat flux from the surface (H). Since incoming radiation did not change, the decrease in H was mostly compensated for by an increase in E (caused by the increased water vapor gradient between the surface and the air resulting from increased canopy temperatures) and by a small increase in

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upwelling longwave radiation (*LWU*). Aerodynamic resistances were typically low during the day (< 10 s/m) so the surface was closely coupled to the air above it.

At night, however, T_m and the *LWD* forcing contributed about equally to the change in surface temperature for nights with lower wind speeds (e.g. Figure 1, ~120 hour). At night the temperature gradient is reversed ($T_m > T_a$) from that of the day so, in contrast to midday, by increasing T_m the temperature gradient is increased. Aerodynamic resistances are larger at night (>100 s/m) causing the surface to be more uncoupled from the air above it and increasing T_m further increased atmospheric stability. The 23 Wm^{-2} increase in *LWD* represents a 25% change in net radiation at night versus 5% change during midday.

These responses are summarized in the comparison of [n] DTR (Equation 2) shown in Table 1. The impacts of *LWD* forcing alone produces a significant change in the DTR relative to the mean temperature while increasing T_m or the combination of increasing T_m and *LWD* have only small impacts on [n] DTR.

Surface Conductance Parameterization

A pair of simulations were run in which canopy g_c was *i*) allowed to decrease in response to a doubling of atmospheric CO_2 as reported by Sellers et al. (1996c) (see Equation (1)) resulting in ~25% decrease in midday g_c, and *ii*) held constant over the course of the diurnal cycle as is the case for so called bucket models that do not include a diurnal physiological response (see Sellers et al., 1997). In the former case, E decreases by as much as 10% at midday compared to the case where T_m and *LWD* was increased without stomatal response to high CO_2, but surface air temperatures increased only by about 0.1K because of the strong coupling between the surface and air allowing increased H to compensate for the lower E. In the latter case in order to mimic the bucket model approach, g_c was fixed for the whole diurnal cycle at a value to matched midday E in the control (using Equation 1). At night, the fixed g_c scenario caused excessive E

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by as much as 50 W m^{-2}, reducing temperatures by up to 2 K and thus increasing the DTR

relative to the control. Table 1 shows that a fixed gc produces a significant increase in the

Δ DTR. Stomatal response to high CO_2 combined with increased T_m and *LWD* had virtually no

effect on the Δ DTR.

Vegetation Parameters

The two of the most influential vegetation parameters in SIB2 are V_m which specifies the

maximum capacity of the canopy for photosynthesis and, therefore, the maximum canopy

conductance capacity; and *FPAR*, which represents the fraction of incident *PAR* absorbed by the

canopy. V_m is analogous to the maximum canopy conductance parameter used in other

biophysical landsurface models, and is reduced by water stress and extreme temperature stress.

FPAR is mostly a function of the amount of green leaves (*LAI*), solar illumination angles and

canopy structure. We examine the sensitivity of the DTR to the value of the maximum capacity,

specified in practice by the initial prescription of the parameter and by its reduction as a result of

physiological stress. Effects of prescribed *FPAR* are also examined.

Reducing V_m by 50% caused a 30% reduction in g_c at midday, and a decrease in peak ΔE by

about 25%. T_a at midday increases by up to 0.5 K. Strong midday stomatal closure occurred in

the low V_m simulation indicating a positive feedback between stomatal closure, surface humidity

and T_a (Equation (1), Collatz et al. 1991). The warming occurred only during the day, causing

the *DTR* to increase (Table I). The large change in the DTR relative to the mean air temperature

caused the Δ DTR to significantly increase. This implies that an increase in V_{max} or conductance

capacity would cause a significant decrease in Δ *DTR*. Water and temperature stress would

have the effect of reducing V_{max} or conductance capacity thus potentially increasing the *DTR*.

Reducing *FPAR* by 50% caused peak conductances to decrease by 33%, and reduced peak ΔE

by over 25% from the control. This led to an increase in T_a at midday of about 0.5 K, similar to

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the low V_m simulation. Here again, the [n] DTR increased dramatically as a result of the change in a parameter of the model showing the importance of the vegetation boundary conditions of the model in determining the response of the DTR.

V Conclusions

The following general conclusions can be drawn from these results:

•   An increase in LWD raised nighttime temperatures thus reducing the DTR while changes in T_m or $T_m + LWD$ increased both the maxima and minima with only small effects on the DTR. This response was largely driven by diurnal variability in aerodynamic stability and net radiation.

•   Maintaining g_c constant over the diurnal cycle as in the case of bucket type models will cause the DTR to be larger than when more realistic, diurnally varying g_c responses are used.

•   All physiological forcings (g_c, V_m and $FPAR$) produced changes in the DTR that were large relative to the mean temperatures. This implies that errors in parameterizations of landsurface models will introduce errors in predicted [n] DTR, a conclusion also supported by our GCM simulation in which we reduced physiological stress. These results suggest that reported increases in vegetation cover during the 1980's (Myneni et al. 1997) could have lowered the DTR during the growing season even as mean temperatures increase by increasing   E during the day, decreasing stability at night and through the influence of increased   E on atmospheric water vapor content and cloudiness.

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Figure Legend:

Figure 1. Canopy air space temperature for control (black) , 3.2 K increase in driver temperatures (red), 23 W m^{-2} increase in down-welling longwave radiation (blue) and increases in both temperature and down-welling longwave (green).