Modeling the effects of historical vegetation change on near-surface atmosphere in the northern Chihuahuan Desert

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ABSTRACT

Our goal was to evaluate effects of broad-scale changes in vegetation from grasslands to shrublands over the past 150 years on near-surface atmosphere over the Jornada Experimental Range in the northern Chihuahuan Desert, using a regional climate model. Simulations were conducted using 1858 and 1998 vegetation maps, and data collected in the field. Overall, the vegetation shift led to small changes in sensible heat (SH) and an increase in latent heat (LH). The impacts of shrub encroachment depended on shrubland type: conversion from grass to mesquite cools the near-surface atmosphere and from grass to creosotebush warms it. Higher albedo of mesquite relative to grasses reduced available energy, which was dissipated mainly as LH due to the deeper root system in mesquite. In creosotebush-dominated areas, a decrease in albedo, an increase in roughness length and displacement height contributed to the SH increase and warmer temperatures. Sensitivity simulations showed that an increase in soil moisture content enhanced shrub LH and a reduction in mesquite cover enhanced the temperature differences. The observed shift in vegetation led to complex interactions between land and surface fluxes, demonstrating that vegetation itself is a weather and climate variable as it significantly influences temperature and humidity.

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1. Introduction

Observations and modeling studies show that changes in land–surface properties can influence the near-surface atmosphere through exchanges of heat, moisture, momentum, gases, and aerosols on timescales ranging from seconds to years, and on local to global spatial scales (Foley et al., 2003; Pielke, 2001; Pielke et al., 1998; Pitman, 2003). Deforestation, afforestation, desertification, cultivation, and irrigation are landscape modifications that often lead to changes in near-surface fluxes that may affect weather and climate with feedbacks to the vegetation (see Pielke et al., 1998, for a listing of published work related to these research topics).

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A key example of landscape change involves woody plant invasion into perennial grasslands and has occurred in arid and semiarid regions globally over the past several centuries. In the Chihuahuan Desert of North America, shrub cover has increased dramatically in areas that were predominantly grassland in the mid-1800s (Buffington and Herbel, 1965; Gibbens et al., 1992, 2005). Since the early 1900s, C_3 shrubs, mesquite (*Prosopis glandulosa*) and creosotebush (*Larrea tridentata*), have increased in cover at the expense of C_4 grasses, mainly black grama (*Bouteloua eriopoda*) (e.g., Figs. 1 and 4). For example, in 1858, grasses comprised more than 80% of the Jornada Experimental Range (JER) in the northern Chihuahuan Desert (Gibbens et al., 2005). By 1998, 59% of the area is now occupied by mesquite and 25% is dominated by creosote with only 7% grass cover. Overgrazing combined with extreme drought are two factors that have contributed to these changes (Buffington and Herbel, 1965; Grover and Musick, 1990; Neilson, 1986; Peters, 2000; Schlesinger et al., 1990).

Structural changes of the land surface have occurred as a result of this shift in plant dominance with potential effects on climate with feedbacks to the vegetation. Surface and vegetation characteristics affected by this shift include albedo, leaf area, roughness length, and root biomass distribution (Asner and Heidebrecht, 2005; Gibbens et al., 1996). These changes can potentially alter surface latent and sensible heat (SH) fluxes with feedbacks to the biophysical variables (Pitman, 2003). A positive feedback is illustrated by the impact of albedo on precipitation. An increase in albedo could decrease precipitation through its effect on the surface fluxes, which leads to declines in soil moisture, therefore eventually increasing the albedo, reducing the net radiation, that could decrease sensible and/or latent heat (LH), leading to a decrease in clouds, with further reductions in precipitation. This land cover-atmospheric feedback is proposed as one of the processes that can explain desertification dynamics (Charney, 1975; Peters et al., 2004; Schlesinger et al., 1990).

Several observational and modeling studies have found different effects of grass or herbaceous reduction in cover (i.e., overgrazing, drought) on near-surface fluxes and temperature. One set of studies (e.g., Charney, 1975; Charney et al., 1977; Otterman, 1974, 1989) showed that higher albedo in response to vegetation removal led to less available energy to heat the atmosphere, thus producing cooler temperatures. Another set of studies, along the Mexico–USA border in the Sonoran Desert, also showed a 5% higher albedo on the overgrazed Mexican side relative to the adjacent vegetated area in Arizona (Balling, 1988; Bryant et al., 1990). However, the low vegetation cover on the Mexican side, with 29% more bare soil than in Arizona, increased LH flux (i.e., soil evaporation and transpiration) for the first few days after a rain event. After a few days, transpiration in the more heavily vegetated area on the US side drew on remaining subsurface infiltrated rainfall, and the vegetated area had a greater LH flux. Initially, the less vegetated side had cooler surface temperatures and about the same air temperatures than the more vegetated side. However, after the initial period, the air temperatures on the US side were markedly cooler (Warner, 2004). This contrasting behavior in fluxes and temperature with respect to the increase in albedo can be attributed to differences in soil moisture content, vegetation cover, and roughness length between the two studies.

Due to the highly complex interactions between plants, soils, and atmosphere, observational studies provide a contemporary and limited view of the myriad of land–atmosphere interactions occurring in these semiarid ecosystems. Fully coupled atmospheric–biospheric models constitute a powerful tool for addressing the effect of historical vegetation changes on the near-surface atmosphere. With these models, plants and atmosphere are nonlinearly interacting with each other.

The objective of this study was to examine the effects of historical vegetation changes that have occurred on the JER on near-surface latent and SH fluxes and the resultant temperature and humidity using a three-dimensional coupled plant–atmospheric model. We used vegetation maps estimated from survey notes and color infrared aerial photographs from Gibbens et al. (2005) for 1858 and 1998 to carry out modeling simulations. In addition, we evaluated the sensitivity of initial soil moisture conditions and mesquite cover on the partition of available energy and the role of albedo on model results.

2. Experiments and data

2.1. Overview of the models

We used the fully coupled atmospheric–biospheric model GEMRAMS, that is comprised of the Colorado State University version of the Regional Atmospheric Modeling System 4.3 (RAMS; Cotton et al., 2003; Pielke et al., 1992) and the General Energy and Mass Transport Model (GEMTM; Chen and Coughenour, 1994; Eastman et al., 2001a). GEMRAMS has been used to study the effects of land-cover change and CO_2 on weather and climate for the central Great Plains, Australia and southern South America (Beltrán 2005; Eastman et al., 2001a, b; Narisma and Pitman, 2004; Narisma et al., 2003).

RAMS is a general-purpose, atmospheric-simulation model that includes the equations of motion, heat, moisture and continuity in a terrain-following coordinate system. RAMS also includes a soil–vegetation–atmosphere transfer scheme, the Land Ecosystem-Atmosphere Feedback model version 2 (LEAF-2) (Walko et al., 2000) that represents the storage and exchange of heat and moisture associated with the vegetation, canopy air, and soil. Temperature, precipitation, humidity, winds, as well as surface energy fluxes (i.e., LH and SH) are predicted by RAMS. LH is composed of the heat required by physical evaporation (e.g., from soils and leaf surfaces) and transpiration through the stoma of leaves, while SH is the transfer of heat directly by temperature.

GEMTM is an ecophysiological process-based model that can be used to simulate the interactions between the atmosphere and the growing canopy (Chen and Coughenour, 1994). The main feature of GEMRAMS is that the atmosphere

and biosphere are allowed to dynamically interact through the surface and canopy energy balance. Interactions between transpiration, photosynthesis, and root water uptake are represented explicitly in GEMRAMS. In other words, LEAF-2 uses the value of leaf area index (LAI) and canopy conductance computed by GEMTM, through photosynthesis calculations, to estimate canopy transpiration. Evaporation is assumed to occur from the top soil layer only.

2.2. Model configuration

The experiments were set up with one grid, centered on the JER site (32°37′N, 106°44′W), New Mexico, USA with 50×50 grid points and a horizontal grid increment of 1 km (Fig. 1). There are 60 vertical levels that extend to about 23 km above the ground and 12 soil layers down to a depth of 4 m. The vertical grid spacing varies from 80 m near the surface, with the first model level at 40–800 m at the top of the domain. The time step for the model integration is 10 s. The simulations were set up with the following options: no precipitation processes were activated, only condensation was allowed; Mellor and Yamada (1982) parameterization for vertical diffusion; modified Smagorinsky (1963) scheme for horizontal diffusion; lateral boundary conditions according to Klemp and Wilhelmson (1978); for top boundary conditions, a Raleigh friction layer was specified on the top 20 grid points; radiation scheme according to Chen and Cotton (1983).

Land-cover data for the domain were obtained from vegetation maps for 1858 and 1998 based on Gibbens et al. (2005) for the JER site (Fig. 1) (Peters et al., 2006). For the purpose of these simulations, the different species of grass and shrubs were grouped into four vegetation classes based on the dominant species in a $1 \text{ km} \times 1 \text{ km}$ pixel: black grama grass (dominated by *B. eriopoda*), mesquite (*P. glandulosa*), creosotebush (*L. tridentata*), and tarbush (*Fluorensia cernua*) classes. For the 1858 vegetation map, yucca (*Yucca elata*) and other shrub-free cells were grouped into an "other grasses" type. The grid cells outside the JER site necessary to completely cover the $50 \text{ km} \times 50 \text{ km}$ simulation area were classified as semiarid,
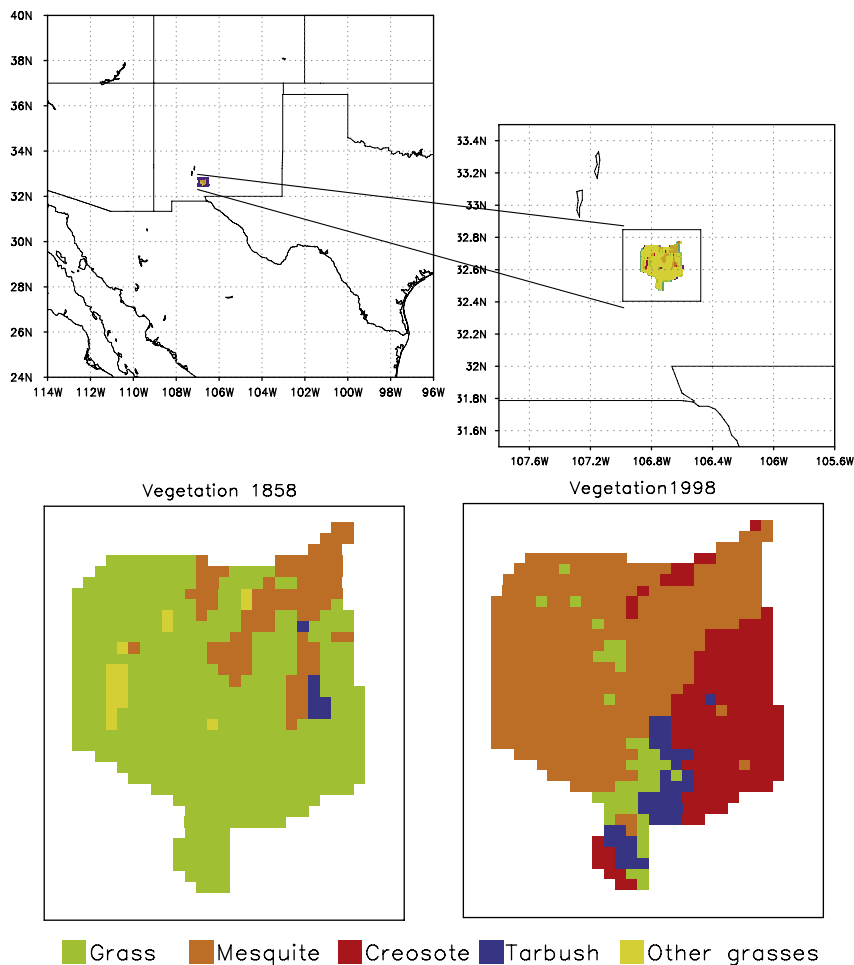

Fig. 1. Location of the Jornada Long-Term Experimental Range site, the GEMRAMS model domain for the simulations (top), and the vegetation distribution in 1858 and 1998 (bottom). Each grid cell is 1 km × 1 km.

according to the Global Ecosystems dataset (Olson, 1994). This land-cover type outside the JER area was kept the same for the 1858 and 1998 vegetation maps.

GEMRAMS uses the USDA soil texture classes (USDA, 1993) for soil types. A soil texture class was associated to a given vegetation type and assigned to each grid cell of the simulation domain. We used the following vegetation–soil texture relations: grass and mesquite were associated with loamy sand, and tarbush and creosotebush with silt loam and sandy loam, respectively. Values from Cosby et al. (1984) were used for the soil thermal and hydrological parameters.

Parameters values derived for each vegetation type were assigned to each group based on observed data (unpublished data) and on RAMS default land-use classification for the grid cells outside the core area (Table 1). Initial conditions for GEMRAMS also included root distributions for each vegetation type (Fig. 2), based on published and unpublished data (H. Johnson and R.P. Gibbens, personal communication; Moorhead et al., 1989).

Initial atmospheric conditions are given by horizontally homogeneous vertical profiles of temperature, relative humidity and wind speed, derived from the National Center for Environmental Prediction (NCEP) reanalysis (Kalnay et al., 1996). All the simulations performed had the same initial atmospheric conditions. We chose two clear and calm days in May and August 2002, as representative of mid-spring and late-summer atmospheric conditions. The simulations started at 6:00 Mountain Standard Time (MST) and lasted 20 hours.

2.3. Experimental design

In order to examine the effects of vegetation change on near-surface atmospheric conditions, and the sensitivity of model results to soil moisture and mesquite cover, pairs of simulations were performed using a single vertical profile corresponding to two dates as initial atmospheric conditions. Within a given pair, one run used 1858 vegetation distribution and the other used 1998 vegetation. The "control" experiments (CTRL) used average initial soil moisture conditions based on neutron probe measurements of volumetric soil moisture content for each of the vegetation types (Snyder et al., 2006) (Fig. 2).

Additionally, a total of nine pairs of sensitivity tests to soil moisture initial conditions and to mesquite cover were performed to evaluate their effects on the partition of available energy and the role of albedo on near-surface energy fluxes and temperature changes. Four pairs of sensitivity tests to initial soil moisture conditions, using both 1858 and 1998 vegetation maps, were conducted using four different soil moisture profiles. A "dry" condition (DRY) used a soil moisture profile that was 20% drier than the control run conditions throughout the whole profile. The DRY sensitivity experiments could represent the system several days after a precipitation event. We used three different wetter-than-control experiments, increasing soil moisture and wetting depth. Typical summertime precipitation events would be the situation associated with the WET and WETT_sfc experiments. These events are usually of short duration and generally wet only the top-most soil layers in arid and semiarid systems (Sala et al., 1992). In these two experiments, the top 90 cm was 20% and 50% wetter the control run (WET and WETT_sfc, respectively), while the rest of the layers had the same soil moisture values as the control run. In a third "wetter" simulation, soil water content of the entire profile was increased by 50% with respect to the CTRL run (WETT_all). A wet winter condition is represented by the WETT_all experiments where wetting occurs in deep soil layers during longer duration winter precipitation events (Sala et al., 1992). We consider the WETT_all experiment as an extreme situation after a rainfall event; in this ecosystem water is mostly distributed on the top 40 cm with a low number of cases with water reaching depths lower than 80 cm (for example, see Reynolds et al., 2000).

We also performed five pairs of sensitivity experiments to mesquite cover within grid cells. For these simulations, the mesquite cover was 25%, 50%, 75%, 125%, and 150% of the percentage of cover assumed in the CTRL simulations (Table 1).

Although we considered a relatively simple case of only 2 days with no cloud cover, the simulation results for the CTRL and all sensitivity experiments are intended to show direction of changes and spatial patterns of near-surface fluxes, temperature and humidity associate with the heterogeneous characteristics of the vegetation changes within this JER domain. This approach has also been used in other historical land-cover changes simulation studies (e.g., Schneider et al., 2004). Another consideration is that we have used a "semiarid" type for the vegetation outside the core area. Although the results from the "control" simulations could be influenced by the parameter values chosen for that vegetation, we have analyzed the simulation experiments in terms of "differences" between "actual" and "historical" vegetation patterns.

Table 1
Parameter values for the vegetation types

Vegetation types	LAI ($m^2 m^{-2}$)		Vegetation cover (%)		Albedo		Roughness length (m)	Displacement height (m)
	May	August	May	August	May	August		
Grass	0.8	0.8	25.1	41.8	0.25	0.21	0.018	0.120
Other grasses	0.3	0.3	15.0	15.0	0.27	0.27	0.018	0.120
Mesquite	1.1	0.9	16.8	22.5	0.34	0.35	0.060	0.467
Creosotebush	1.6	0.9	36.5	37.5	0.24	0.28	0.060	0.760
Tarbush	1.4	0.8	28.7	32.4	0.22	0.24	0.050	0.433
Semiarid	1.2	1.2	23.4	23.4	0.25	0.25	0.053	0.353

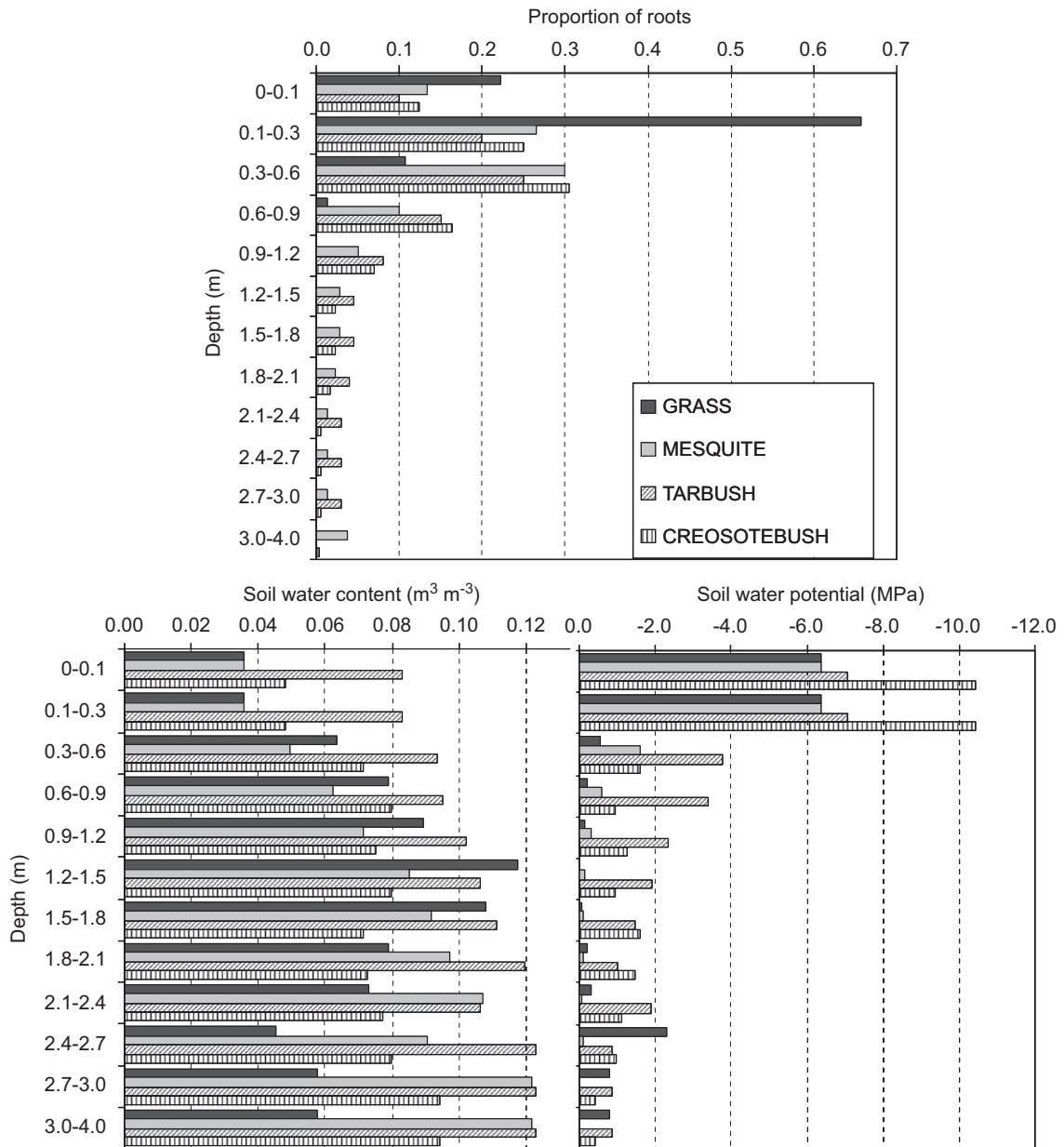**Fig. 2.** Root profile for the vegetation types considered in this study (top). Initial soil water content ($m^3 m^{-3}$) (left bottom) and soil water potential (MPa) (right bottom).

We would not expect the results (i.e., the "differences") to be very much affected by the vegetation parameters outside the core area, since only near the edges of the core area should horizontal advective effects be significant.

　　To our knowledge this is the first time these two land-cover maps are used to perform this kind of simulations. This work will increase our understanding of the potential effects of historical vegetation changes on the near-surface atmosphere in this area.

3. Results and discussion

　　In this section, we describe LH and SH fluxes, and near-surface temperature and humidity resulted from the CTRL simulations (Section 3.1) and sensitivity experiments (Sections 3.2 and 3.3). Results are shown in terms of spatial distribution of daytime averages (7:30 MST–19:30 MST) and at 12:00 MST, and area-averages.

3.1. Control simulations

3.1.1. Surface energy fluxes average conditions

Overall, lower values of LH than SH (Table 2) were the result of the combined effect of low soil moisture content, low LAI and low vegetation cover (Table 1). LH represented an average 27% of SH. In our simulations, more than 65% of the LH flux corresponded to soil evaporation. This value is higher than those observed by Dugas et al. (1996) and Schlesinger et al. (1987), which ranged between 30% and 60%. However, Reynolds et al. (2000), in a modeling study, found that evaporation from soil represented 66% of the annual LH flux, which ranged between 40% and 99%. Bowen ratio values ($\beta =$ SH/LH), computed from the daytime area-averages, ranged from 3.0 to 4.3 (Table 2). These values are within the typical Bowen ratio range of 3–6 for a semiarid area (Oke, 1993).

The simulated SH and LH fluxes for each vegetation type are within the range of measured values reported by Dugas et al. (1996), Rango et al. (1998), and Prueger et al. (2004) for a variety of locations inside the JER site, and smaller than the SH+LH values observed by Small and Kurc (2003) for the Sevilleta National Wildlife Refuge in central New Mexico (Table 3).

The spatial patterns of SH and LH reveal that even in this small simulation domain differences exist among vegetation types (Fig. 3 and Table 2). SH was greatest in creosotebush (southeast portion of the domain in the SH 1998 map) and lowest in mesquite (western and northeastern portions of the SH 1998 map) mainly due to differences in albedo (see Table 1). The lowest values of LH, on average, corresponded also to creosotebush. The highest value was found in tarbush, and maybe caused by the relatively high values of soil moisture (Fig. 2). Among vegetation types, the relatively range of variation in LH was much higher than in SH, 21% and 163%, respectively (Table 3). Dugas et al. (1996) found similar values for SH and lower values for LH, 24% and 92%, respectively (Table 3).

3.1.2. Surface energy fluxes changes due to historical vegetation variations

The shift between the two different 1858 and 1998 vegetation scenarios (see Figs. 1 and 4), with their associated soils and distinctive structural and physiological vegetation characteristics, resulted in changes in near-surface fluxes, temperature and humidity. When averaged over the grid cells in the JER domain, LH increased an average of 24% from 1858 to 1998 (Table 2). Changes in SH were of opposite sign in May and August simulations, 4% decreased and 3% increased, respectively (Table 2). Similar values were also found at 12:00 MST. These values indicate an overall change in how the energy is partitioned between LH and SH in the area, as it is evident in the decreased of Bowen ratio from 1858 to 1998

Table 2
Daytime area-averaged and 12:00 MST values of sensible (SH) and latent (LH) heat (W m^{-2}) for the CTRL case (and for August and May experiments between parentheses)

Year	Daytime average	12:00 MST
1858		
SH	176 (194–158)	317 (333–300)
LH	43 (48–37)	60 (70–50)
β	4.1 (4.0–4.3)	
1998		
SH	177 (201–153)	317 (342–292)
LH	53 (54–51)	74 (78–69)
β	3.3 (3.7–3.0)	

The Bowen ratio (β) was computed based on the daytime area-averaged values of SH and LH.

Table 3
Sensible (SH) and latent (LH) heat (W m^{-2}) area-averaged values at 12:00 MST for each vegetation group for the CTRL case (and for August and May experiments between parentheses)

	SH		LH		SH+LH[a]			
	Simulated	Observed[b]	Simulated	Observed[b]	Clear days		All days	
					Wet	Dry	Wet	Dry
Grass	317 (331, 303)	299	52 (62, 42)	62	508	469	443	426
Mesquite	298 (324, 271)	273	83 (90, 75)	70				
Creosotebush	360 (287, 333)	329	46 (45, 47)	61	413	386	381	358
Tarbush	318 (331, 305)	339	121 (111, 130)	117				

[a] From Small and Kurc (2003). Average between 10:00 and 15:00 MST during May–October of 2000 and 2001 at the Sevilleta National Wildlife Refuge, New Mexico.
[b] From Dugas et al. (1996). Averages from Bowen ratio estimations between 11:30 and 12:00 MST for 33 days during April–November of 1991 and 1992 at locations inside the JER site.
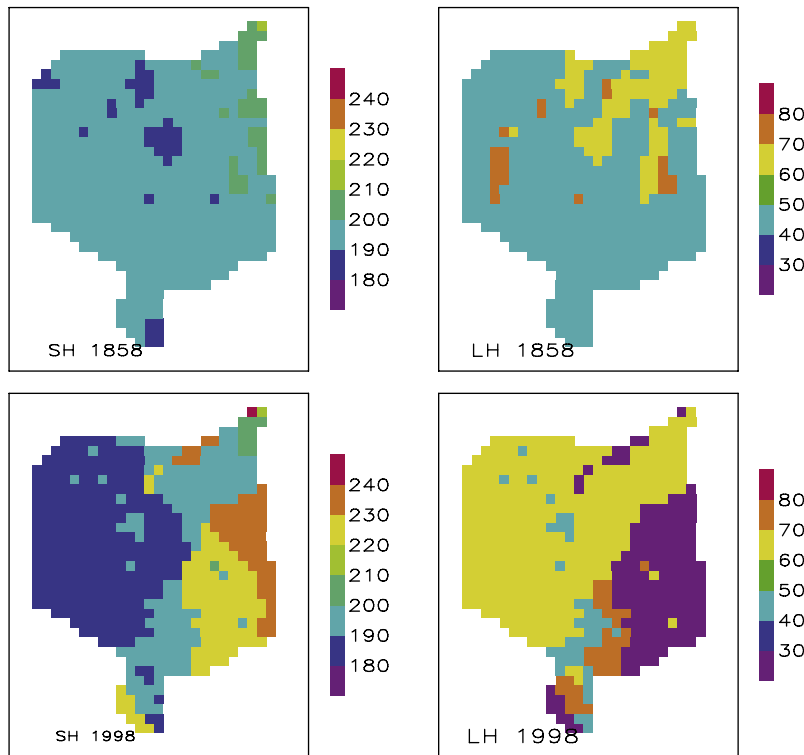
Fig. 3. Daytime average of sensible (SH) and latent (LH) heat fluxes (W m^{-2}) for 1858 (top) and 1998 (bottom) conditions for the CTRL May experiment.

(Table 2). The decrease in Bowen ratio indicates that, over the domain, relatively more heat is now being used in transpiration and evaporation than in heating the atmosphere, with more water being added to the atmosphere and a cooling effect associated with both processes. This suggests that, as a result of the vegetation change, the near-surface atmosphere of the area would be cooler and wetter in a shrub-dominated 1998 than in a grass-dominated 1858.

Examination only of area-averaged values of changes in the fluxes could be misleading because spatial differences in surface energy fluxes between 1858 and 1998 are noticeable (Fig. 3). Fig. 4 shows the vegetation changes occurred between 1858 and 1998 and the simulated differences in SH and LH at 12:00 MST. The two main conversions were from grass to mesquite on the west side of the domain, representing 48% of the grid cells, and from grass to creosotebush on the southeast area, with 22% of the grid cells changed. Grid cells exhibiting similar vegetation changes were grouped and differences in the average fluxes between 1858 and 1998 were calculated (Table 3).

The different biophysical and physiological characteristics of the vegetation associated with the changes can help to explain the spatial variability in the simulated fluxes. Two main patterns can be recognized (Fig. 4). First, SH decreased and LH increased on the west side of the domain, where a conversion from grass to mesquite occurred. The higher average albedo of the mesquite area relative to grasses reduced the available energy. The simulated increase in LH flux was mainly due to an increase in transpiration (not shown) associated with the deeper root profile in mesquite than in the grasses; the available energy is being dissipated mainly as LH, so SH flux decreased. Second, on the east side of the domain, SH clearly increased in the conversions from grass or mesquite to creosotebush, 12% and 20% in average respectively (Table 4). Higher SH in the grass-to-creosotebush conversion may be associated with an increase in the roughness length (from 0.018 to 0.060 m) and displacement height (from 0.12 to 0.76 m) because changes in albedo were not so noticeable. Increase in SH associated with the mesquite to creosotebush change may be attributed to a decrease in albedo.

Changes in LH on the east side depended on the type of the vegetation conversion and the simulated day. LH decreased an average 45% (Table 4) in the small area that converted from mesquite to creosotebush for both simulated months, mainly due to a decrease in transpiration. Volumetric soil moisture contents were slightly higher in creosotebush than in mesquite, but due to the sandy-loam soil texture, soil water potentials of creosotebush were much lower than mesquite (Fig. 2) and therefore transpiration was limited in creosotebush. Changes in LH were subtle in the grass to creosotebush conversion area on the east side. Furthermore, the direction of change differed between May and August (Table 4 and Fig. 4). The decrease in LH was due to a decrease in evaporation (not shown), which may be associated with the combined effects of increased in vegetation cover and a soil texture change, similar to the mesquite to creosotebush conversion.

In the small area that changed from grass to tarbush, there was a slight variation in SH, but the increase in LH was the largest among all the vegetation conversions, an average of 67 W m^{-2}, representing an increase of 134% (Table 3). In this case, physical evaporation increased more than transpiration, due to higher soil water content.
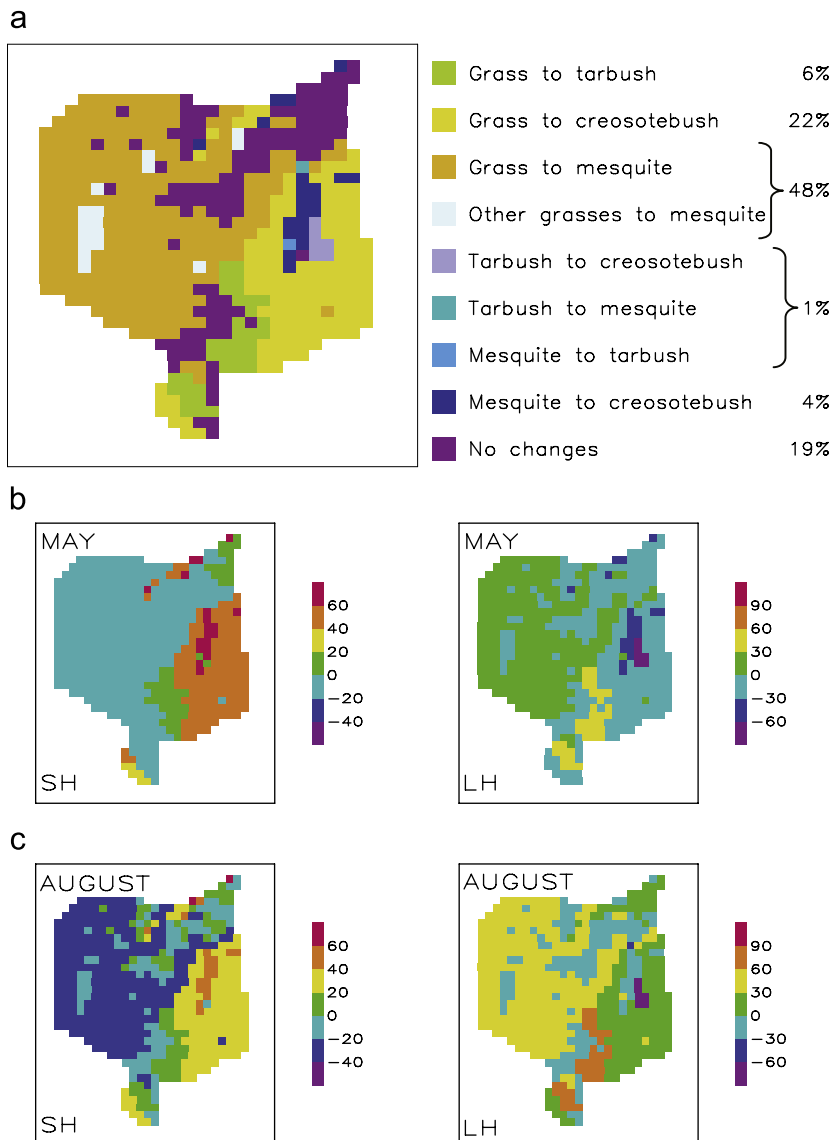
Fig. 4. (a) Vegetation changes occurred between 1858 and 1998 at the Jornada Long-Term Experimental Range. The fraction of grid cells with the corresponding vegetation change is shown on the right. (b) Differences in sensible (SH) and latent (LH) heat fluxes (W m^{-2}) between 1998 and 1858 at 12:00 MST for CTRL May runs; (c) Idem (b) for August runs.

Table 4
Changes (1998–1858) in sensible heat (SH) and latent heat (LH) at 12:00 MST for the CTRL case for August and May experiments for the main vegetation changes (see Fig. 4)

	SH				LH			
	May		August		May		August	
	12:00 MST	%	12:00 MST	%	12:00 MST	%	12:00 MST	%
Grass to mesquite	↓ −10	−3	↓ −33	−11	↑ 26	40	↑ 32	77
Grass to creosotebush	↑ 50	15	↑ 23	8	↓ −18	29	↑ 3	7
Grass to tarbush	≈0	0	↑ ≈1	0	↑ 47	73	↑ 87	200
Mesquite to creosotebush	↑ 61	19	↑ 58	21	↓ −47	−51	↓ −29	−38

SH and LH values are in W m^{-2}. Also the relative changes (%) between 1998 and 1858 relative to 1858 are shown.

3.1.3. Near-surface temperature and humidity changes

Changes in near-surface fluxes modified near-surface air temperature and humidity (Fig. 5). The near-surface atmosphere tended to be cooler and more humid with shrub-dominated vegetation than with the historic grass-dominated vegetation. The area-averaged differences are small (Fig. 5) but, like the modeled changes in surface fluxes, they are spatially heterogeneous. The analysis of the simulated 2 m temperature at 12:00 MST showed warmer temperatures (up to 0.8 °C) on the east side of the domain and cooler temperatures (up to −0.6 °C) on the west side of the domain (Fig. 5), consistent with an increase and decrease, respectively, of SH (see Fig. 4 and Table 4). Temperatures decreased when grasses were converted to mesquite or tarbush. Conversely, temperatures increased when either grass or mesquite was replaced with creosotebush (see also Fig. 7). At the first model vertical level (approximately 40 m), differences become smaller and influenced by the background flow, but the spatial pattern remains. Changes in vapor mixing ratio and relative humidity are less noticeable. Nevertheless, an increase and decrease in humidity are found on the west and east side of the domain, respectively, associated with the corresponding changes in the LH flux (Fig. 4).

In our simulations, conversion of grasses to shrubs produced a heterogeneous response in fluxes and temperature. Changes in SH fluxes from 1858 to 1998 are largely due to changes in albedo: increases in albedo led to a decrease in SH. Our results agree with the findings of Otterman (1974) and Charney et al. (1977). Roughness length and displacement
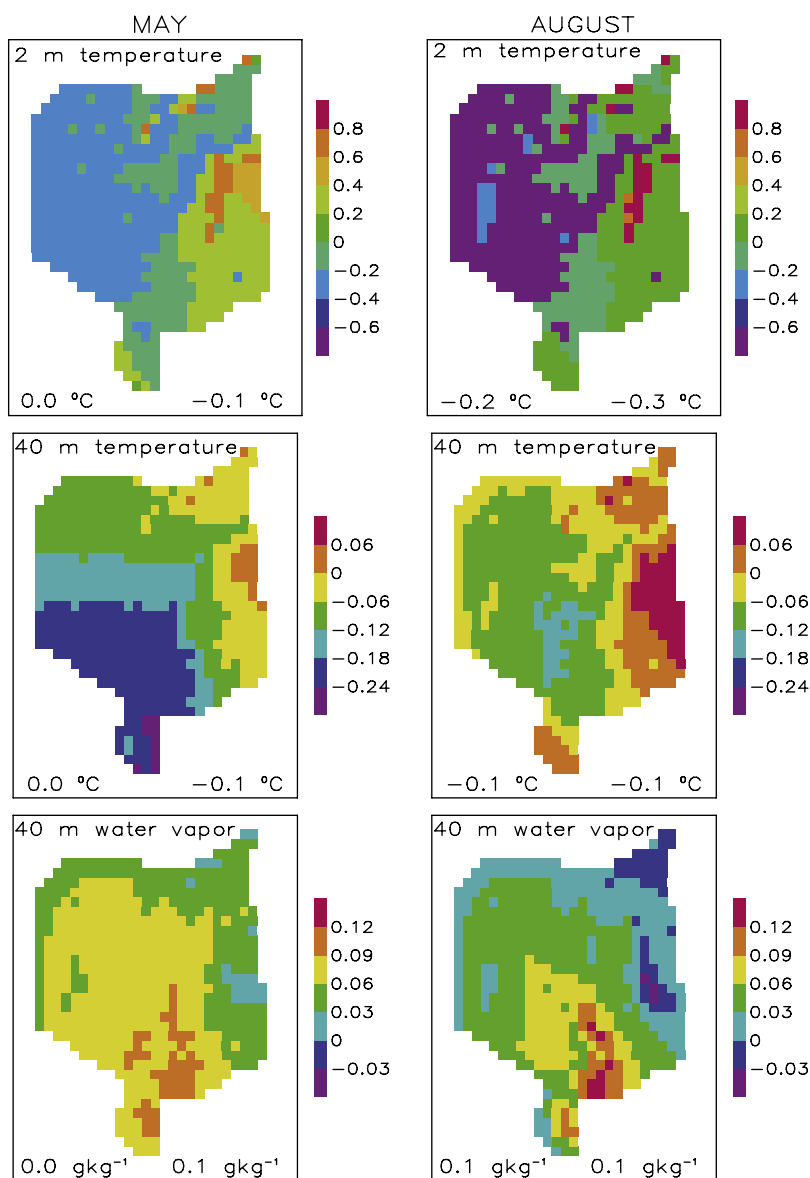

Fig. 5. Differences between 1858 and 1998 at 13:00 LST for 2 m temperature (°C) (top); first model level temperature (°C) (middle); water vapor mixing ratio (g kg⁻¹) (bottom). The area-averaged differences at 12:00 MST (left) and the diurnal average (right) are shown in each figure.

height are additional factors that may explain the increase in SH in the cells that converted from grass to creosotebush, where changes in albedo were not large. Isolating the factors affecting the changes in LH can be more complex because of the two different processes involved, transpiration and evaporation. In our simulations, changes in LH from 1858 to 1998 can be attributed to changes in rooting depth, different physiological response to soil water content, changes in soil texture, and changes in soil moisture. Nevertheless, the changes in LH were relatively higher than in SH. Changes in sensible and LH fluxes acted in the same direction to affect the near-surface temperature: lower (higher) SH and higher (lower) LH produced cooler (warmer) temperatures.

3.2. Sensitivity to soil moisture initial conditions

In semiarid areas, soil moisture content can have a strong effect on the surface fluxes, and in available energy partitioning (see Table 3 and Small and Kurc, 2003). In our sensitivity simulations to soil moisture content we varied the soil moisture in the profile (i.e., drier and wetter than the CTRL runs) and the wetting depth. The sensitivity simulations showed that SH and LH were, respectively, higher and lower than the CTRL case in the DRY experiment (Table 5). On the other hand, increasing initial soil moisture (WET and WETT experiments) decreased SH and increased LH with respect to the CTRL run. The sign of the changes was consistent in both May and August runs (Table 5). In all experiments, absolute differences were similar between SH and LH (i.e., from 11 to 34 $\mathrm{W\,m^{-2}}$ in SH, and from 8 to 53 $\mathrm{W\,m^{-2}}$ in LH), but relative changes in LH were higher than in SH. A 50% increase in initial soil moisture conditions in the first 90 cm (WETT_sfc) led to an average 55% (maximum 104%) change in LH but only an 11% (up to 16%) change in SH, with respect to the CTRL run (Table 5). When more water was also available in the deeper soil layers (below 90 cm, WETT_all experiments) LH increased up to an average of 80% (maximum 135%).

Spatial heterogeneity in this set of sensitivity experiments was also noticeable and consistent with the area-averaged values. Fig. 6 shows as an example the differences for the CTRL August run for the DRY and WETT_all experiments. Within each sensitivity experiment, changes in SH and LH were consistent for all vegetation conversions. The grass to tarbush conversion (center-south part of the simulation domain, see Fig. 4) presented the highest sensitivity to changes in soil moisture, following by grass to creosote and grass to mesquite (Fig. 6). Changes in LH were mostly a consequence of changes in soil evaporation (not shown), but the contribution of transpiration to LH increased with the initial water content. Although in the WETT_sfc experiment LH increase for grasses was lower than for mesquite (not shown), transpiration for grasses was more responsive than transpiration for mesquite. Increasing deep soil water content slightly increased transpiration and LH (Fig. 6) in all shrubs.

The differential behavior of grasses and shrubs in response to soil moisture conditions affected the differences in SH and LH fluxes between 1858 and 1998. Overall, dry conditions tended to enhance the differences in SH flux and attenuate them in the case of LH flux: the area-average absolute differences were larger and lower than the CTRL run for SH and LH fluxes, respectively (Table 6). The opposite behavior was true as the initial soil moisture conditions increased: SH and LH differences between 1858 and 1998 decreased and increased, respectively, over all the entire study area (Table 6).

Spatially, the differences in the fluxes between 1858 and 1998 for changing soil moisture conditions were consistent with the sensitivity found with respect to the CTRL run (Fig. 6): grass to tarbush conversion presented the highest differences in the energy fluxes, following by grass to creosote and grass to mesquite (not shown). In particular, for all the cells converted from grass to shrubs, both transpiration and evaporation contributed to the increase in LH.

The effect of these changes in the 2-m temperatures is shown in Fig. 7 for the main vegetation conversions. Consistent with the energy fluxes trends, as the soil becomes wetter, the differences become larger, i.e., more negative, for the areas converted from grass to shrubs. On the other hand, differences in temperature become smaller, or less positive, for the area converted from mesquite to creosotebush. The response is non-linear in the case of grass to mesquite conversion.

Table 5
Differences in sensible heat (SH) and latent heat (LH) between the soil moisture sensitivity experiments (DRY, WET, WETT_sfc, and WETT_all) and the CTRL run

	SH			LH	
	Average	%		Average	%
DRY—CTRL	11 (3, 10)	3		−11 (−13, −10)	16
CTRL	**317 (338, 296)**			**67 (74, 60)**	
WET—CTRL	−12 (−12, −12)	−4		8 (8, 9)	12
WETT_sfc—CTRL	−34 (−38, −30)	−11		44 (44, 44)	66
WETT_all—CTRL	−34 (−38, −30)	−11		53 (48, 57)	80

The values in bold for the CTRL run are the SH and LH area-averaged values at 12:00 MST (and for May and August runs between parentheses). All LH and SH values are in $\mathrm{W\,m^{-2}}$. Percentage with respect to CTRL is also shown.
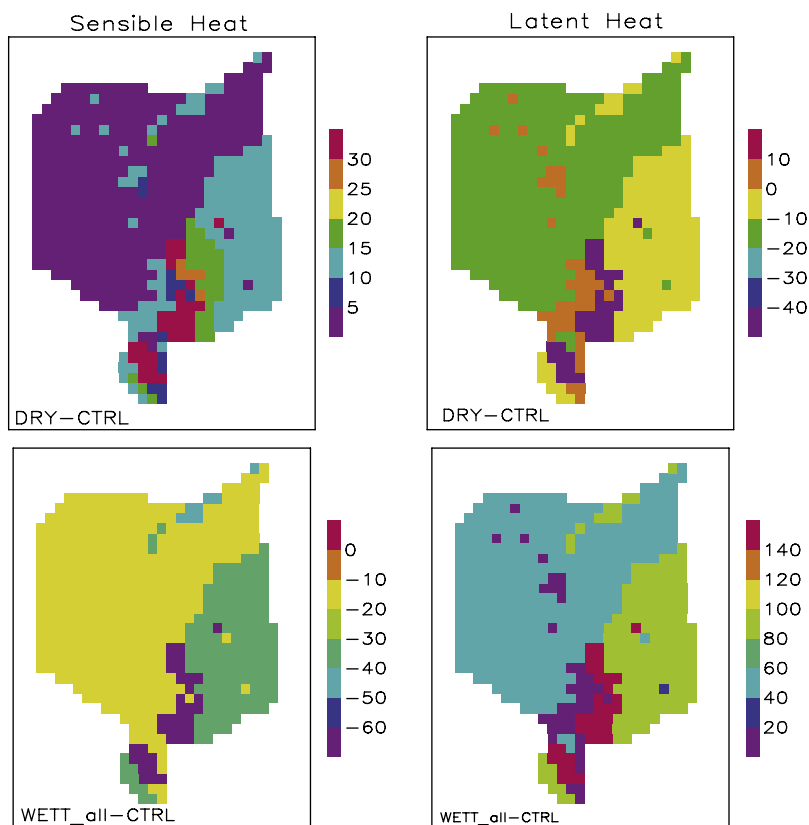
Fig. 6. Differences of the 1998 August run daytime averaged sensible (right) and latent heat (left), between each sensitivity experiment and the control run (CTRL) for DRY (top) and WETT_all (bottom). Values are in W m^{-2}.

Table 6
Changes (1998– 1858) in area-averaged sensible heat (SH) and latent heat (LH) at 12:00 MST for the soil moisture sensitivity experiments: DRY, WET, WETT_sfc, and WETT_all and the CTRL run (values are in W m^{-2})

	SH		LH	
	12:00 MST	%	12:00 MST	%
DRY	5 (20, −10)	0	−3 (−7, −2)	−4
CTRL	1 (9, −8)	0	14 (8, 19)	25
WET	0 (8, −8)	0	29 (24, 34)	51
WETT_sfc	−29 (−26, −31)	−10	73 (70, 76)	101
WETT_all	−30 (−27, −11)	−10	83 (75, 91)	109

The May and August values are shown in parentheses. The relative changes in SH and LH fluxes (%) between 1998 and 1858 relative to 1858 are also shown.

As the initial soil water conditions decrease, the temperature differences in the latter case are similar or become more negative than the CTRL run, depending on the day (Fig. 7).

The largest sensitivities to soil moisture in energy fluxes and temperature among the simulations occurred between the WET and WETT_sfc experiments, when initial soil water content increased from 20% to 50% in the first 90 cm of the soil profile (Tables 5 and 6). This indicates a direct effect of increased soil moisture in transpiration and evaporation processes. On the other hand, increasing the wetting depth, as from the WETT_sfc to WETT_all experiments, did not substantially affect SH, although LH differences were still noticeable (i.e., slight increased) (Tables 5 and 6). In this case, the assumed root systems of grass and shrubs are mostly responsible for this behavior: the deeper root system in shrubs allows them to access deeper soil moisture not available for grasses. In our simulations, we assumed that grasses have their root profile above 90 cm, and 40%, 20%, and 16% of the roots in tarbush, mesquite, and creosotebush are below 90 cm (Fig. 2). The largest sensitivity in energy fluxes and temperature found in the grass to tarbush conversion area is consistent with their different root system.
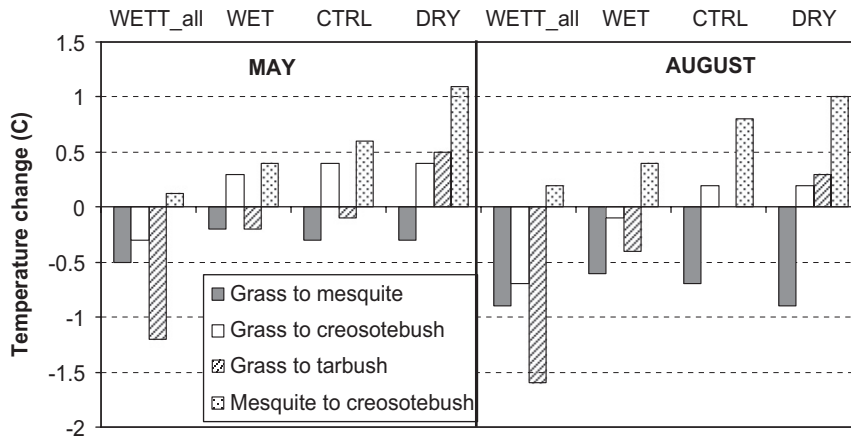
Fig. 7. Differences in 2-m temperature between 1998 and 1858 at 12:00 MST averaged for the main four vegetation conversion types for the soil moisture sensitivity experiments (WETT_all, WET, and DRY) and the control run (CTRL) for May and August.
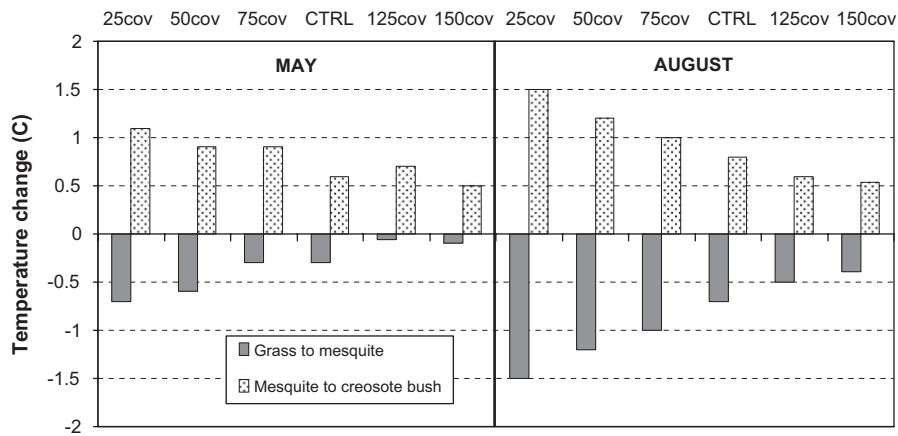

Fig. 8. Differences in 2-m temperature between 1998 and 1858 at 12:00 MST averaged for the main four vegetation conversion types for the mesquite vegetation cover sensitivity experiments (25cov, 50cov, 75cov, 125cov, 150cov) and the control run (CTRL) for May and August.

3.3. Sensitivity to changes in mesquite cover

One of the proposed mechanisms of increased temperature in overgrazed areas is that the low vegetation cover reduces the LH and, as a result, ground and air temperature increase. We found that varying the amount of ground cover by mesquite mainly affected albedo. As the percentage of soil covered by mesquite decreased (e.g., more bare soil), the absolute changes in albedo between 1858 and 1998 became larger. Then, in the areas that changed from grass to mesquite, where albedo increased from 1858 to 1998, the albedo increased more, up to 50% in the August run, leading to an enhanced reduction in SH and in temperature (Fig. 8). On the other hand, in the few grid cells that changed from mesquite to creosotebush (where albedo decreased) SH and temperature increased. From 1858 to 1998, cooling in the grid cells that changed from grass to mesquite became larger, while the opposite in the mesquite to creosotebush conversion (Fig. 8). The differences in temperature between 1858 and 1998 decreased as the percentage of area covered by mesquite increased.

In several studies of desertification effects (e.g., Charney et al., 1977; Otterman, 1989), a complete removal of the vegetation, with bare soil or desert-like land-cover is assumed. Shrub encroachment increased the percentage of bare soil, but the soil was still covered by some percentage of vegetation (Table 1). In these 1-day simulations, increased albedo as a result of changes in vegetation cover was the dominant factor controlling fluxes and temperature. Drier conditions in the soil than the one assumed here, where evaporation was suppressed, could possibly reverse the effect, although we found a dissimilar response to the decrease in soil moisture.

4. Summary and conclusions

We used a coupled atmospheric-vegetation model to examine how observed changes in vegetation from grasslands to shrublands could potentially affect the near-surface energy balance, temperature and humidity with feedbacks to the

vegetation. Our simulations showed that the change from an 1858 environment, dominated by grasses, to a 1998 area mostly covered by shrubs, led to an overall decrease of SH and a pronounced increase of LH. Overall, a simulated shift in the energy partition from SH to LH resulted in a cooler and moister low atmosphere, which would be expected to alter vegetation species competition over a longer time period. We also found that the response was spatially heterogeneous and associated with physical and physiological characteristics of the soils and vegetation. On the west side of the domain, temperatures were cooler with the current mesquite cover, associated with an increase in LH and decrease in SH. Higher albedo of mesquite relative to grasses reduced the available energy, that was dissipated mainly as LH due to the deeper root system in mesquite. On the other hand, on the east side of the domain, temperatures were warmer over the area now covered by creosotebush, due to a clear increase in SH. In this case, not only a decrease in albedo but also an increase in roughness length and displacement height may have contributed to the increase in SH. Albedo changes induced by land-cover modifications played a major role in near-surface atmospheric processes.

We also performed sensitivity simulations to the initial soil moisture conditions and to percentage of mesquite cover. In all cases, soil evaporation contributed more than transpiration to changes in LH. Latent Heat fluxes responded more than SH fluxes to an increase in soil moisture content. Under wet conditions, we found cooler temperatures in 1998 than in 1858 in most of the domain. Under dry conditions, this created a warmer eastern domain, except for the grid cells converted from grass to mesquite, where temperatures were still cooler over grass. Changes in mesquite cover affected the albedo, enhancing the differences in temperature between 1858 and 1998 found in the CTRL run.

Through all the experiments performed in this study, we found that the impacts of shrub encroachment on surface fluxes and temperature depended on the particular characteristics of the "shrub" considered: conversion from grass to mesquite cools the near-surface atmosphere and conversion from grass to creosotebush warms it. The different vegetation conversions encompass a wide range of biophysical and physiological changes. Many of the modeling or observational studies dealing with effects of land degradation/landscape modifications/land-use and vegetation changes on surface fluxes have been based on cases of "extreme" changes: complete removal of the vegetation (vegetated areas vs. bare soil), irrigated vs. non-irrigated areas, lakes vs. bare soil/grassland, cropland vs. natural vegetation, that implied very different characteristics for each of the land cover analyzed. Here, we found subtle changes in temperature and fluxes considering the landscape as a whole, although changes were spatially more important. Furthermore, initial soil moisture conditions strongly influenced the results.

The shift from grasslands to shrublands observed in this area has led to complex interactions between biophysical and physiological characteristics of the land and surface energy fluxes. These results clearly demonstrate that vegetation itself is a weather and climate variable as it significantly influences near-surface temperature and humidity. These changes may then feedback and affect the vegetation. This view supports the broader view of climate that is reported in the National Academy of Sciences report (NRC, 2005).

Acknowledgments

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