The Impact of a 2 × CO_2 Climate on Lightning-Caused Fires

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ABSTRACT

Future climate change could have significant repercussions for lightning-caused wildfires. Two empirical fire models are presented relating the frequency of lightning fires and the area burned by these fires to the effective precipitation and the frequency of thunderstorm activity. One model deals with the seasonal variations in lightning fires, while the second model deals with the interannual variations of lightning fires. These fire models are then used with the Goddard Institute for Space Studies General Circulation Model to investigate possible changes in fire frequency and area burned in a 2 × CO_2 climate. In the United States, the annual mean number of lightning fires increases by 44%, while the area burned increases by 78%. On a global scale, the largest increase in lightning fires can be expected in untouched tropical ecosystems where few natural fires occur today.

1. Introduction

During the dry months of the year, large areas of the world have a heightened potential for the ignition and development of fires. Decreases in precipitation, accompanied by increases in temperature, reduce soil moisture, causing root systems and surface fuels to dry, with resultant systematic dehydration from roots through canopy of underbrush and low vegetation.

Currently, the large majority of fires around the globe are a result of anthropogenic activity, dominated by fires associated with tropical deforestation. However, as one moves from the Tropics to middle and high latitudes, the importance of natural lightning-caused fires increases. In the United States, lightning fires make up only 10% of the total number of fires annually, but result in 48% of the area burned (USDA Forest Service 1992). However, in some local regions in the western United States, lightning fires make up more than 80% of the fires. In Canada, 35% of the fires are caused by lightning, resulting in 85% of the area burned (Stocks 1991). Lightning fires tend to cause more damage than man-made fires because these fires often occur in remote regions that are difficult to reach by fire crews. In addition, lightning fires often start simultaneously at a few different locations, spreading the resources available to fight the fires. It is estimated that a half-million lightning discharges strike the world's forests each day (DeCoursey et al. 1983). Even when conditions are too moist for ignition to occur, lightning can still damage trees resulting in the enhanced spread of insects and disease.

The occurrence of natural forest fires depends on a combination of three factors: climatic conditions, fuel loading, and ignition sources. Given sufficient fuel, the primary prerequisite for ignition is fuel dryness, followed by ignition sources. For example, in the tropical rain forests where fuel is abundant and lightning storms are frequent, few natural fires occur due to the moist climate (Fearnside 1990). On the other hand, in drier midlatitude regions where lightning and fuel are less abundant, lightning fires are dominant in some regions (Barrows 1978). Moreover, in the southeast United States, which is normally moist, the fire frequency increases when dry conditions prevail, whereas in California, which is dry, fire frequency increases when the frequency of thunderstorms increases.

Much interest has been focused recently on the possibility of future climate change influencing the frequency and intensity of wildfires. Paleoclimatic records show large increases in fire activity during warm, dry climatic conditions (Clark 1988). In addition, dry spring conditions in the southwestern United States, associated with La Niña–Southern Oscillation events, are well correlated with enhanced fire activity in those regions (Simard et al. 1985; Swetnam and Betancourt 1990). If future climate change results in changes in thunderstorm and drought conditions, lightning fires may be influenced significantly.

The few studies that have been conducted on the relationship between fire activity and future climate change all show increases in the severity of fires as a result of a warmer climate (Street 1989; Flannigan and Van Wagner 1990; Torn and Fried 1992). However,

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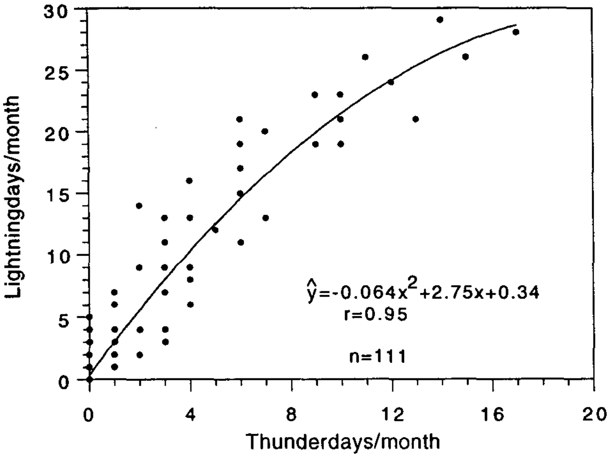

FIG. 1. Relationship between observed thunder days per month and observed lightning days per month in region 3.

none of the studies consider possible changes in ignition sources as climate changes, and none of them differentiate between natural and man-made fires. Furthermore, no study deals with the possible changes in the number of fires in a warmer climate, and no study has considered natural fires on a global scale.

In this study, the Goddard Institute for Space Studies (GISS) General Circulation Model (GCM) is used to investigate how changes in both the hydrological cycle and thunderstorm activity may affect the frequency and intensity of future lightning-caused fires around the globe.

2. Fire models

To study the relationship between lightning fires, climate, and thunderstorm activity, monthly climatological data from the southwestern United States (region 3 of the U.S. Forest Service: Arizona and New Mexico) were analyzed. This region of the United States has the largest concentration of lightning fires as a result of the synergistic influence of lightning storms, a dry climate, and fuel availability.

On a monthly scale, the meteorological parameters best related to fire occurrence are those related to water balance, since water balance is closely related to fuel moisture (Bradshaw et al. 1983; Clark 1989). Water balance, also known as effective precipitation, is simply the difference between precipitation and potential evapotranspiration. Precipitation is the atmospheric supply of moisture to the surface, whereas potential evapotranspiration is the atmospheric demand of moisture from the surface. These parameters, together with thunderstorm and fire statistics, were analyzed for a period of 15 years (1960–74) in order to develop climatological relationships between effective precipitation, number of thunderstorms, number of fires, and area burned by these fires. These monthly fire data are taken from Barrows (1978).

Thunder days are defined as days when thunder is audible at a specific meteorological station, corresponding to an area of approximately 2000 km^2 around the station. This is obviously always less than the actual number of thunderstorms in the study region. This is shown in Fig. 1, where the number of thunder days (audible) is correlated with the number of lightning days (visible). These data are taken from the local climatological records from two stations in the southwestern United States (Albuquerque and Phoenix) for the period 1960–65. Unfortunately, since 1966, the local climatological data does not report lightning days but only thunder days. Note that many of the points in Fig. 1 overlap with each other.

The time series of the four parameters of interest in this study are shown in Fig. 2. The time series shows data from all twelve months of the years. Potential

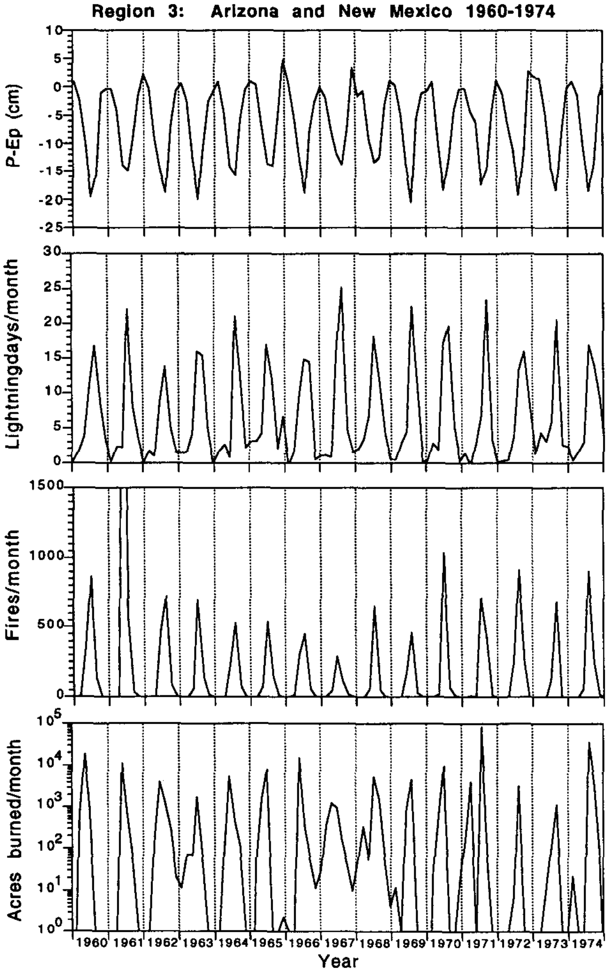

FIG. 2. Monthly observations of effective precipitation ($P - Ep$), lightning days, number of fires, and area burned in region 3 of the U.S. Forest Service (Arizona and New Mexico) from 1960–74.

evapotranspiration is calculated using the Thornthwaite (1948) method that uses temperature data to approximate the atmospheric demand of moisture. Other more exact methods of calculating this parameter cannot be used due to the lack of the appropriate climatological data. Lightning days were obtained using the thunder day statistics and the curve in Fig. 1. Fire frequencies are high, resulting in large areas burned, during the summer months when effective precipitation ($P - Ep$) has large negative values and the thunderstorm activity is frequent.

Using the parameters in Fig. 2, multivariate regressions could be obtained from the data. By using all data points (15 years × 12 months), a model that describes the seasonal variability of fire activity is obtained. The seasonal relationships between the number of fires per month and area burned per fire, and the two dependent variables, $P - Ep$ and lightning days, are presented in Fig. 3. The family of solid lines represents the number of lightning fires per month (F_t) and lies on a plane described by

$$F_t = -63.75 - 21.95P_e + 8.13L \quad (R = 0.56)$$
$$n = 180, \quad p < 0.001, \quad (1)$$

where L = lightning days per month and P_e = monthly mean effective precipitation [$P - Ep$ (cm)]. The family of dashed lines represents the acres burned per fire (A_t) and lies on the plane described by

$$A_t = 3.02 - 1.74P_e - 1.21L \quad (R = 0.45)$$
$$n = 180, \quad p < 0.001. \quad (2)$$

Given any value of L and P_e, the number of lightning fires and the total area burned per month can be calculated. Although these two relationships are highly significant at the 99.9% level, the two relationships describe only 31% and 20% of the variance, respectively.

There are a few possible explanations as to why these correlation coefficients are not larger. First, the model parameters (P_e and L) are not directly observed but rather inferred from other parameters (temperature and thunder days), which themselves may not be representative of the spatial and temporal heterogeneity of the region under consideration. In addition, using temperature and thunder days to infer P_e and L introduces additional noise associated with these relationships into the model. Second, the observed fire parameters [number of fires (F) and area burned (A)] may also have inherent problems, such as nondetection of small fires and the suppression of natural fires resulting in less area burned than expected. Furthermore, the mean area per fire is obtained using the total area burned per month and the total number of fires per month. This value is probably different to what would be found if the area burned for each fire was known. Third, the model does not include additional parameters that may be important in predicting monthly fire activity, such as wind speed, relative humidity, and vegetation type. All these factors may influence the relationships presented above.

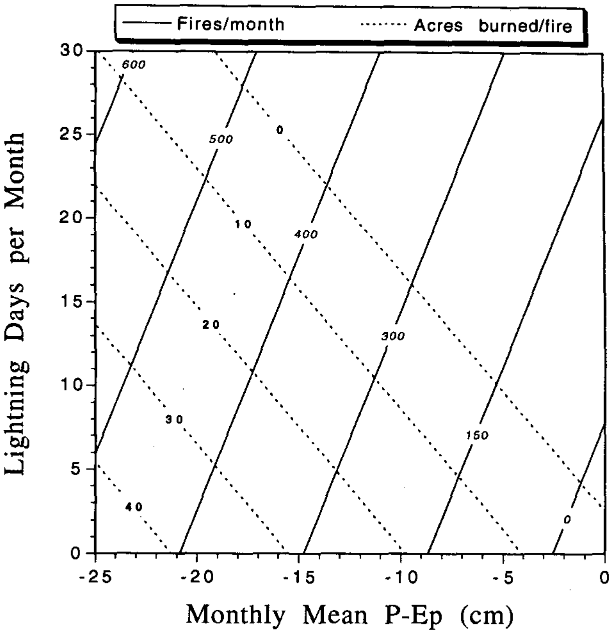

FIG. 3. Seasonal model: multivariate relationships between number of lightning days per month, monthly mean effective precipitation, number of fires per month, and acres burned per fire in region 3. Solid and dashed lines are described by Eqs. (1) and (2).

The validity of the above seasonal model depends on the assumption that the 180 months of data are all independent from each other. To check for serial independence, the time series of the residuals (predicted–observed) is plotted in Fig. 4. The lag 1 autocorrelation of the residuals is 0.13 for the fire model and 0.02 for the area model. These autocorrelations are insignificant, implying that the use of all data in developing this model is justified.

By using only the data points from the peak of the fire season (May, June, and July), a model is obtained that describes the interannual variability of fire activity. During these three months of the year, observations show that 77% of the lightning fires occur in this region (Arizona and New Mexico), corresponding to 95% of the area burned.

The interannual relationships between number of fires per month and area burned per fire, and the two dependent variables, $P - Ep$ and lightning days, are presented in Fig. 5. The family of solid lines represents the number of lightning fires per month and lies on a plane described by

$$F_t = -81.24 - 39.97P_e + 4.59L \quad (R = 0.85)$$
$$n = 45, \quad p < 0.001. \quad (3)$$

The family of dashed lines represents the acres burned per fire and lies on the plane described by

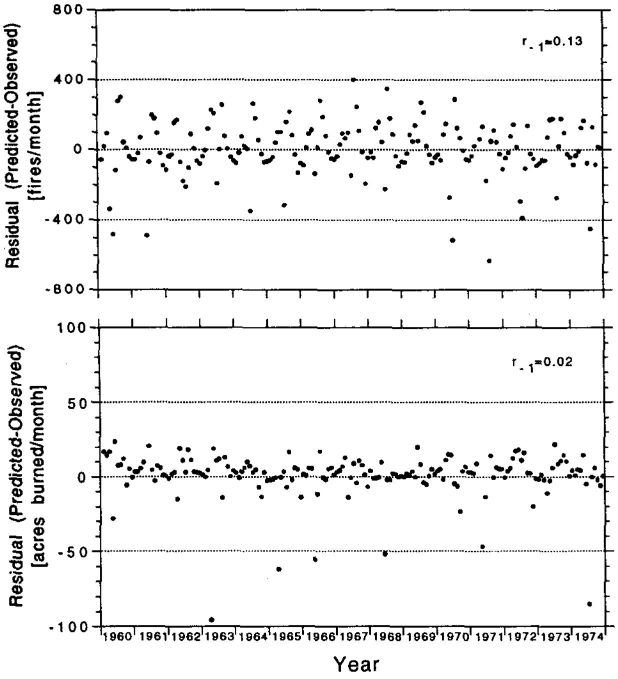

FIG. 4. Time series of the residuals from (a) annual fire model and (b) annual area model. The lag 1 autocorrelation coefficient is shown for each time series.

$$A_t = -27.7 - 5.09P_e - 2.27L \quad (R = 0.44)$$
$$n = 45, \quad p < 0.001. \quad (4)$$

Both of the above two relationships [Eqs. (3) and (4)] are also highly significant at the 99.9% level, with the interannual fire model explaining 72% of the variance, while the interannual area model explains only 19% of the variance.

The reason that the area burned per fire is less predictable than the number of fires is probably due to the fact that lightning ignited fires occurring before 1974 were not left to burn freely. Therefore, depending on location, manpower, and budget, fires could burn different sized areas even if the atmospheric parameters were the same. Furthermore, as mentioned above, parameters that are not included in the models, such as wind, humidity, and vegetation, may also influence the area burned by lightning fires.

The above two models were developed for an area of approximately 22 million acres of land protected by the U.S. Forest Service (region 3 USDA Forest Service). Any use of these models in other regions, as discussed below, should be calibrated according to the area of the region under consideration.

When studying the possible effects of future climate change on fire frequency and severity, the interannual model needs to be used [Eqs. (3) and (4)]. For this model, if the number of thunderstorm days per month is held constant, then every 1 cm decrease in effective precipitation results in an extra 40 fires per month. In addition, this same decrease in $P - Ep$ results in a 5.1 acre increase in the area burned per fire, resulting in a total of 204 additional acres burned per month. This is largely due to vegetation burning more efficiently as the fuel moisture decreases.

If $P - Ep$ is held constant, then for every additional day with thunderstorm activity, an extra five fires occur per month. However, the extra fires with the same water balance results in a 2.3 acre decrease in the area burned per fire. This is possibly due to the fact that more fires are competing for the same area of vegetation, or more likely that the increased thunderstorm activity results in more precipitation that wets fuel and prevents the spread of fires.

If both the thunderstorms increase and the effective precipitation decreases by one unit each, the number of fires per month increases by 45, and the area burned increases by 2.8 acres per fire.

Similarly, on a seasonal timescale (Fig. 3), if the lightning days increase and the effective precipitation decreases by one unit each, the number of fires per month increases by 33, while the area burned increases by 0.5 acres.

3. Climate model

To estimate alterations in fire frequency and area burned for a future climate, we use the current and doubled CO_2 results from the GISS GCM Model II (Hansen et al. 1983). The model has a horizontal res-

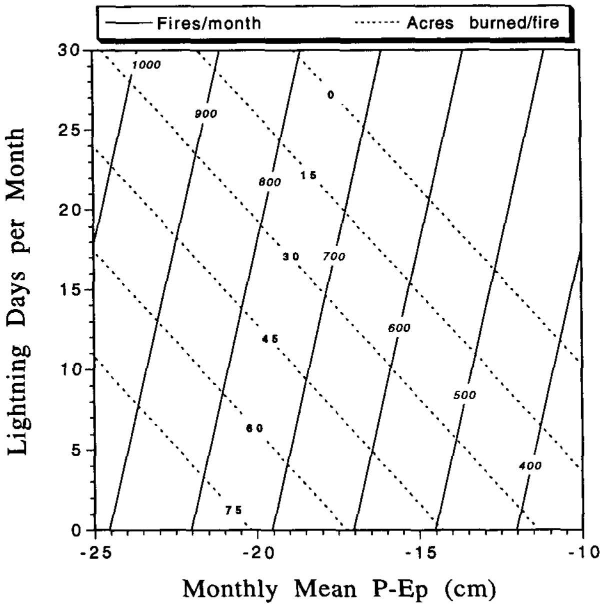

FIG. 5. Interannual model: multivariate relationships between number of lightning days per month, monthly mean effective precipitation, number of fires per month, and acres burned per fire in region 3. Solid and dashed lines are described by Eqs. (3) and (4).

TABLE 1. Monthly climatological values of the number of fires and the acres burned in region 3 from observations, the control run of the GCM, and the model's 2 × CO_2 climate.

	Observations 1960–74 mean		GCM control		GCM 2 × CO_2	
	Fires	Area	Fires	Area	Fires	Area
Jan	0	0	0	0	0	0
Feb	1	5	0	0	0	0
Mar	1	10	21	141	104	141
Apr	14	194	0	0	177	10 123
May	213	4300	117	825	361	9249
Jun	460	14 382	112	621	184	2961
Jul	785	4397	257	4101	365	5735
Aug	298	607	347	6300	413	7042
Sep	106	340	304	4453	371	4453
Oct	14	49	207	13	207	13
Nov	1	10	0	0	0	0
Dec	0	0	0	0	11	0
Total	1893	24 294	1365	16 454	2193	39 717

olution of 8° × 10° (latitude by longitude) with nine layers in the vertical. The physical quantities are calculated at a temporal resolution of 1 h. The model is run for 25 model years before the ocean's mixed layer reaches equilibrium. The model continues running until year 35, and the diagnostics used in this analysis are taken from a 10-year average (years 25–35).

The water balance parameters are calculated directly from the GCM diagnostics of temperature and precipitation. For the 2 × CO_2 climate, the concentration of CO_2 in the model is doubled instantaneously to 630 ppm, and the model is run for an additional 35 years. Most GCMs indicate that as the temperature increases, so does the precipitation (Grotch 1989). However, the increase in potential evapotranspiration due to a warmer atmosphere is far greater than the precipitation increases, resulting in values of $P - Ep$ that become more negative as the climate warms. A 4°C global warming results in a 33% increase in the water holding capacity of the atmosphere. To the vegetation, this alone is equivalent to a 33% decrease in precipitation in our present climate; in contrast, the global precipitation increases by only 12% in the warmer climate.

The lightning diagnostics are calculated using a parameterization developed and discussed by Price and Rind (1992). The parameterization relates the frequency of lightning in thunderstorms to the depth of deep convective clouds. The parameterization is based on the fact that the intensity of updrafts in convective clouds is positively correlated with lightning activity. Intense updrafts lead to the efficient charge transfer between supercooled drops and ice particles in thunderclouds, resulting in clouds with strong updrafts producing more lightning than those with weak updrafts. Since updraft intensity is related to the depth of convective clouds, the height of thunderstorms can often be used to approximate the updraft intensity and, hence, the lightning frequency in thunderstorms.

An additional parameterization was developed to calculate the fraction of cloud-to-ground lightning in thunderstorms (Price and Rind 1993), which is of obvious importance for lightning-caused fires. This parameterization, which is derived from observations of thunderstorms, uses the depth of thunderstorms above the freezing level as an indicator of the fraction of cloud-to-ground lightning in thunderstorms. Therefore, if the total lightning is calculated using the height of the storm, the cloud-to-ground lightning can be calculated if the depth of the storm above the freezing level is also known. The model's control run shows good agreement with global observations of lightning on timescales of diurnal to annual and spatial scales of regional to global (Price and Rind 1994a).

Using Eqs. (3) and (4) in the GISS GCM, we were able to investigate the possible effects of future climate change on lightning fires.

4. Results

a. Southwestern United States

Since the above fire models were developed using data from the southwestern United States, we first looked at the results for this region. Before any future climate experiments can be done, it is first necessary to determine how well the climate model can simulate current fire conditions. For this comparison, the annual fire model [Eqs. (1) and (2)] is used to simulate the present climate's annual cycle of fire activity in this region. The 1960–74 observed monthly mean fire statistics together with the model's fire climatology from the control run are shown in Table 1.

Both the annual number of fires and the total area burned predicted by the model are in good agreement with the observations. However, the distribution of fires and area burned throughout the year derived by the model show some disagreement with actual observa-

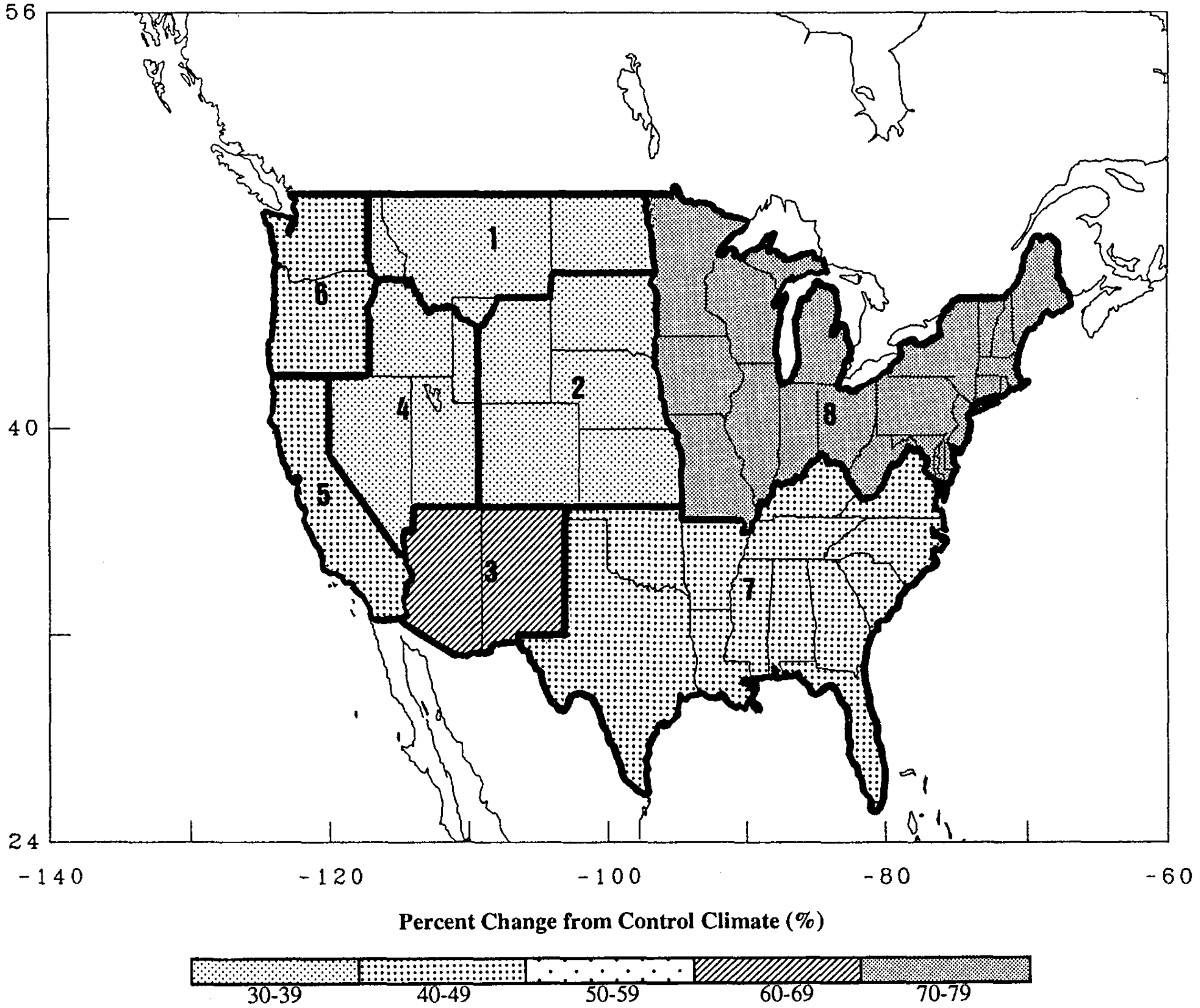

FIG. 6. Regional increases in annual fire frequency across the United States for the 2 × CO_2 climate. The numbers represent the U.S. Forest Service regions considered in this study.

tions. In the model, the distribution of fires is spread fairly evenly over the fire season, while in the observations it peaks in midsummer. The model has the maximum number of fires during August, whereas the observations show a maximum during July. The area burned in the model shows similar problems, with the maximum area burned in August in the model, and not in June as observed. These differences are partly the result of the coarse resolution of the model and partly due to the simplistic ground hydrology in the GCM. The coarse resolution of the GCM results in the smoothing of topographical barriers that shield the southwestern United States from precipitation. This results in too much precipitation throughout the year in the model. However, since the GCM has no real vegetation, the soil moisture decreases rapidly during the summer, resulting in drier conditions than observed at the end of the summer. These deficiencies will be addressed in the next version of the GISS GCM. Furthermore, due to the coarse resolution of the GCM, this region is described by diagnostics from only two grid boxes. Therefore, the signal-to-noise ratio is rather low; to improve the statistics and model climatology, it would be desirable to test these results in a version of the model with finer resolution.

For a 2 × CO_2 climate, which represents a 4.2°C global warming in our model, the annual number of fires in this region increases by 61%, while the annual area burned increases by 141% (Table 1). The largest increases in the frequency of fire and the area burned in this region appear to occur at the start of the fire season in April. However, given the above-mentioned problems with the model's seasonal hydrology, the results for the individual months may be suspect.

TABLE 2. The observed number of fires, the predicted number of fires in the GCM's control run, the predicted number of fires in the $2 \times CO_2$ climate, and the percentage change for the $2 \times CO_2$ climate, for eight regions in the United States.

	1 Northern Region	2 Rocky Mountain Region	3 Southwestern Region	4 Inter-mountain Region	5 Pacific Southwest Region	6 Pacific Northwest Region	7 Southern Region	8 Northeastern Region
Mean number of observed lightning fires ± one standard deviation	710 ± 292	428 ± 96	1606 ± 302	790 ± 281	1466 ± 530	870 ± 557	198 ± 80	42 ± 19
Mean number of lightning fires in control climate	640	476	1365	1737	1173	822	450	258
Mean number of lightning fires in $2 \times CO_2$ climate	859	619	2193	2312	1690	1174	648	456
Percentage change from current climate	+34	+30	+61	+33	+44	+43	+44	+77

b. *United States*

One way of increasing the signal-to-noise ratio is by increasing the sample size. However, the relationships shown in Eqs. (1)–(4) were developed for the southwestern United States and may not be applicable to the entire United States. Unfortunately, fire statistics are generally only reported on an annual basis, and therefore, similar relationships for other regions in the United States cannot be currently obtained. It is possible that since fire frequency and intensity also depend on the type of vegetation available, the relationships presented in this paper may be different in different regions of the United States. However, the general trend of more thunderstorms and drier conditions leading to more fires appears to be fairly robust.

For this reason, the relationships developed for the southwestern United States were used to approximate the fire activity for the contiguous United States, and the model results were compared with annual fire observations. The results for the control run show 6921 lightning fires per year, in good agreement with observations that show 6110 ± 1088 lightning fires per year (USDA Forest Service 1977, 1978, 1980, 1987, 1988, 1989). However, the total area burned in the United States on an annual basis is only 117 368 acres in the GCM compared with observations that show 424 280 ± 360 421 acres burned per year. The observed area burned is highly variable partly as a result of wildfire suppression policies and partly due to the fact that vegetation needs time to regenerate after a fire has occurred. The reason the predicted area burned is less than that observed mean is probably due to the fact that in the United States, the GISS GCM has too much precipitation in the control climate. As mentioned previously, the coarse resolution of the model reduces the height of topographic barriers, resulting in moisture from the Pacific reaching the interior of the United States, increasing precipitation and therefore causing moister conditions than observed. By increasing the resolution of the model, the precipitation on the leeward side of mountains is reduced, and we would therefore expect a reduction of $P - Ep$ in higher resolution models. This would tend to increase the total area burned in the United States during the year.

It should be noted that within the United States there are approximately 15 000 lightning fires each year, resulting in 1.3 million acres burned (USDA Forest Service 1992). However, our study is based on data obtained only for land protected by the U.S. Forest Service.

Although the total number of fires in the United States is in good agreement with observations, some problems exist with the model's results on a regional scale. In Table 2, the observed and modeled annual number of fires in eight regions of the U.S. Forest Service are shown. The geographical distribution of these regions appears in Fig. 6. The GCM predicts too many fires in regions 4, 7, and 8. To understand why these discrepancies occur, it is necessary to look at the individual parameters used in the calculations. Either the model is incorrectly calculating the climatological parameters, or the relationship used to calculate the number of fires is not valid in these regions.

Region 4 in the model appears to have too many thunderstorms during the summer months, while in region 7 the model appears to be too dry and has too many thunderstorms when compared with observations. This leads to an overestimation of the fire frequency in these regions. Region 8 shows wetter conditions than observed. This would appear to inhibit fires and not enhance them. However, the wet conditions that dominate the annual water balance occur in the winter months and not during the fire season. Conditions are drier than observed during the summer and fall months, resulting in more fires than observed. This problem is once again related to the ground hydrology scheme used in the GISS model.

The number of fires in each region for the $2 \times CO_2$ climate, accompanied by the percentage change from the control run, is shown in Table 2 and Fig. 6. These changes were calculated using the interannual model [Eqs. (3) and (4)]. All regions show large increases in the frequency of lightning fires, with the largest changes occurring in the southwestern and the northeastern regions.

The seasonal changes in moisture balance and lightning days in a 2 × CO_2 climate for the entire United States are presented in Fig. 7. Dry conditions are represented by negative values of $P - Ep$. As the climate warms, the effective precipitation decreases during all months, while the number of days with thunderstorm activity increases during most months of the year. This implies increased moisture stress on vegetation, resulting in decreased fuel moisture for live and dead fuels, accompanied by more days with lightning storms. This results in an overall increase in the number of fires and areas burned in the United States.

The seasonal changes in fire activity for the entire United States are shown in Fig. 8. For the 2 × CO_2 scenario, the annual mean changes for the entire United States indicate a 44% increase in the number of fires, with a 78% increase in the area burned. In addition, the length of the fire season is extended in the warmer climate. In the current climate, three months of the year (December, January, February) have no lightning fires and therefore no area burned. In the 2 × CO_2 climate, only January remains without lightning fires.

It should be reemphasized that the relationships used to obtain these estimates will probably differ for different regions of the United States, and errors in the model's climatology make individual monthly results suspect. Nevertheless, we believe the overall trend of more fires, larger areas burned, and longer fire seasons will probably not be altered in more refined models for this magnitude of warming.

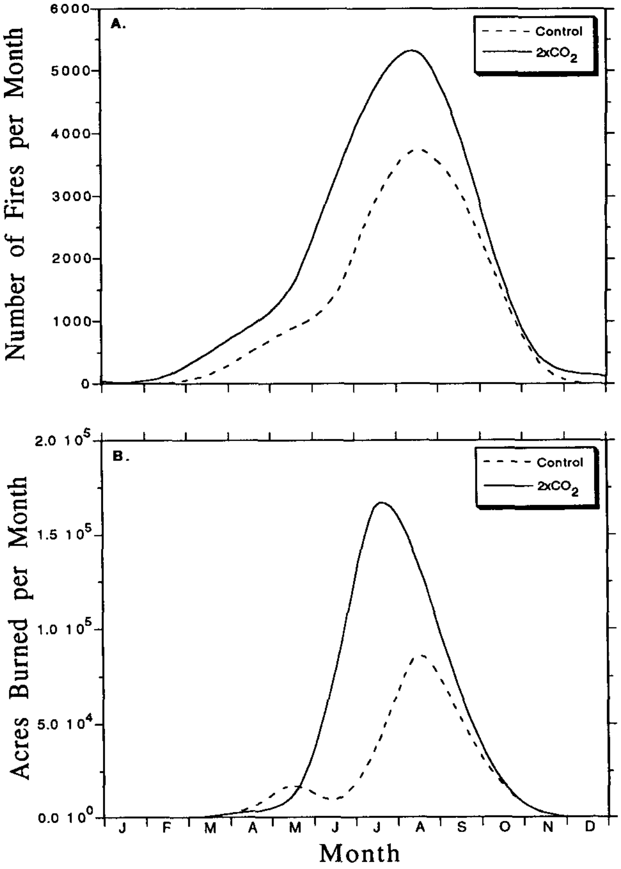

FIG. 8. Monthly results from the control and 2 × CO_2 climates for the United States showing (a) the number of fires per month, and (b) the acres burned per month.

c. Northern Hemisphere fires

Although the relationship between the number of lightning days, effective precipitation, and fires seems to be fairly robust, we are not comfortable extrapolating these relationships to a quantitative fire estimate on a global basis. We therefore only look at how the different parameters change in the 2 × CO_2 scenario on a zonal mean basis.

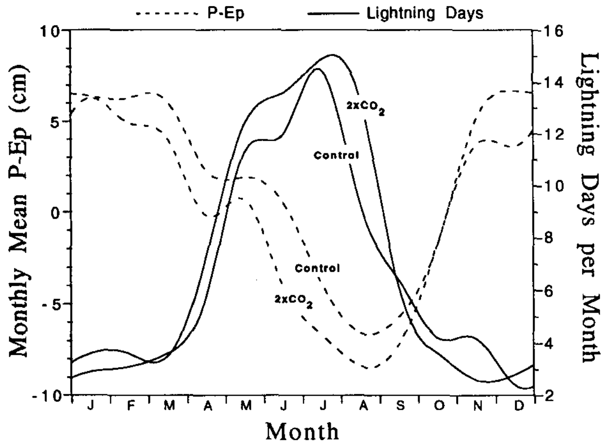

FIG. 7. Monthly values of $P - Ep$ and the number of lightning days in the GISS GCM over the United States for both the control and 2 × CO_2 climates.

The likelihood of future drought in different parts of the world has been discussed by Rind et al. (1990). Using climate change projections for continual exponential growth of atmospheric trace gases, it was found that extreme drought conditions that occur less than 1% of the time in the control run increase in frequency to nearly 50% by the year 2060, the time the global mean temperature has increased by 4.2°C in the model. The increase in the frequency of drought could significantly decrease photosynthesis of vegetation while increasing respiration. A decline in the photosynthesis to respiration ratio will reduce productivity and resistance to insects and disease, resulting in increased stress-induced mortality. This would result in an acceleration in the fuel buildup.

In addition, our climate model studies indicate a 30% increase in global cloud-to-ground lightning activity for a 2 × CO_2 climate, representing a 4.2°C global warming (Price and Rind 1994b). However, over continental regions, a 72% increase is predicted.

The annual mean latitudinal change in temperature, precipitation, potential evapotranspiration, effective precipitation, thunder days, and cloud-to-ground lightning frequencies, over Northern Hemisphere land, is shown in Table 3 (Tropics through midlatitudes). All latitudes experience a decrease in effective precipitation as the climate warms. The largest changes in the moisture balance occur in the Tropics where the water balance goes from being positive in the current climate to negative in the 2 × CO_2 climate. In addition, although the number of thunder days decreases by 2% at 4°N, the frequency of cloud-to-ground lightning increases by 59%. Therefore, even when the number of thunder days decreases, the amount of ignition sources can still increase as a result of more intense thunderstorms (Price and Rind 1994b).

These results imply that if the global climate warms, the largest changes in moisture balance and thunderstorm activity will occur in the Tropics where very few lightning fires occur today. Due to the enormous amounts of available fuel in the tropical forests, this situation could potentially lead to a dramatic increase in tropical lightning fires in the future.

As discussed by Stocks (1991), there is some evidence that high-latitude changes in fire frequency and severity are already occurring. In Alaska, the number of fires from 1949 to 1989 increased by a factor of 5. In Sweden, the number of fires from 1950 to 1979 increased by approximately 50%. In Canada, the number of fires from 1930 to 1990 has increased by approximately 65%, with the major increases occurring over the past 20 years. In addition, in Canada, Russia, and Sweden, the area burned by these fires has steadily increased from 1950 to the present.

5. Discussion

Changes in the frequency and intensity of fires may result in regional as well as global feedbacks on the climate system. Changes in fire frequency can have dramatic effects on the composition of ecosystems, since certain species are more adaptable to changes in fire frequency than others. Tropical rain forests are associated with long natural fire intervals. As fire fre-

TABLE 3. Latitudinal variations of temperature (T), precipitation (P), potential evapotranspiration (Ep), effective precipitation (P − Ep), thunder days (Th), and cloud-to-ground lightning (Lt) for the control run, the 2 × CO_2 climate, and the percentage change from the control climate.

Control climate

Lat	T (°C)	P (cm month^{-1})	Ep (cm month^{-1})	P − Ep (cm month^{-1})	Th (days month^{-1})	Lt (CG month^{-1})
4°N	24.4	15.6	12	3.6	23.6	12 864
12°N	25.0	12.3	12	0.3	12.6	11 136
20°N	24.4	7.5	11.7	−4.2	7.4	8582
27°N	19.3	6.6	9.3	−2.7	4.7	4982
35°N	10.3	7.5	5.1	2.4	3.9	3321
43°N	7.5	6.9	3.6	3.3	3.4	2635

2 × CO_2 climate

Lat	T (°C)	P (cm month^{-1})	Ep (cm month^{-1})	P − Ep (cm month^{-1})	Th (days month^{-1})	Lt (CG month^{-1})
4°N	28.1	17.1	17.4	−0.3	23.2	20 496
12°N	28.9	13.8	17.7	−3.9	13.8	20 160
20°N	28.9	8.4	16.8	−8.4	7.9	13 111
27°N	23.6	7.5	13.5	−6	5.3	7902
35°N	14.8	8.4	8.4	0	5.8	5625
43°N	11.8	7.5	6.3	1.2	4.3	3578

Percentage change (2 × CO_2–control)

Lat	T	P	Ep	P − Ep	Th	Lt
4°N	+15	+10	+45	−108	−2	+59
12°N	+16	+12	+48	−1400	+10	+81
20°N	+18	+12	+44	−100	+7	+53
27°N	+22	+14	+45	−122	+13	+59
35°N	+44	+12	+65	−100	+49	+69
43°N	+57	+9	+75	−64	+26	+36

quency increases, vegetation changes from tropical rain forest to dry forest and eventually to grasslands that experience high fire frequencies (Mueller-Dombois and Goldammer 1990). In addition, modeling studies show that adaptability of different species to changes in fire frequency may completely change the composition of ecosystems (Overpeck et al. 1990; Ryan 1991). In fact, the direct effects of climate change on forest composition may be greatly enhanced by the more drastic effects of climate change on forests due to changes in fire frequency.

Changes in vegetation, as a result of changing fire frequency, can affect the surface albedo on a regional scale. Degradation of vegetation increases the albedo, which reduces the amount of solar radiation absorbed at the surface, and could possibly cool the surface. However, increasing albedo by changing the vegetation also allows a larger portion of the incoming solar radiation to be converted to sensible heat to heat the surface. Potter et al. (1981) showed that increases in surface albedo slightly cool the surface, whereas Xue et al. (1990) show that increases in albedo can result in surface warming. It appears that changes in surface temperature, as a result of albedo changes, depend on whether soil moisture increases or decreases when vegetation is changed or removed (Rind 1984). Observations from China and Brazil show long-term increases in surface temperature and decreases in precipitation as a result of reducing the area of land covered by tropical rain forests, thereby increasing the surface albedo (Wood and Nelson 1991; Li and Lai 1991).

Wildfires are a major source of chemically and radiatively active trace gases, as well as aerosol particles. Some of these trace gases, such as CO_2, N_2O, and CH_4, contribute to the concentration of greenhouse gases in the atmosphere (Crutzen et al. 1979) and therefore may result in a positive feedback on the climate system. These trace gases can remain in the atmosphere from years to decades. On the other hand, aerosol particles emitted from fires can result in a surface cooling by blocking sunlight (Robock 1988) and by increasing the albedo of clouds (Penner et al. 1991). The increase in cloud albedo is due to the increase in the concentration of cloud condensation nuclei (CCN) emitted by fires. For the same liquid water content in clouds, increasing the number of CCN results in a reduction of the mean droplet size, resulting in brighter clouds. However, this process may also result in reduced precipitation from these clouds, which further enhances the existing drought conditions that were needed for the natural fires to occur. Although diffusive clear sky smoke plumes scatter solar radiation back to space, thereby resulting in a net loss of energy to the system, some observations indicate an increase in tropospheric temperatures due to these particles absorbing solar radiation and reemitting infrared radiation (Palmer 1990). However, these tropospheric aerosols remain in the atmosphere for less than a week before they are scavenged by clouds and precipitation and washed out of the atmosphere or deposited through dry deposition. Therefore, at the end of the fire season, these particles are quickly removed from the atmosphere.

Other observed regional feedbacks resulting from increased fire activity are enhanced biogenic soil emissions of NO and N_2O (Levine et al. 1988), enhanced chemical concentrations in lakes and streams (Schindler et al. 1990), and changes in bird populations (Reilly 1991). Furthermore, the plumes that form above fires have been observed to generate lightning that can further ignite additional fires (Latham 1991).

It therefore appears that the effect of increasing frequencies and intensities of lightning fires should result in significant changes in forcings for the climate system, an effect that should not be ignored in subsequent studies. A full accounting of this effect would include changes in the carbon cycle, as well as the aforementioned trace gases and aerosols.

6. Conclusions

This study considers the possible effects of future climate change on natural lightning-caused fires. Local climatological data from the southwestern United States were used to develop relationships between the number of lightning fires and the area burned by these fires, and two dependent variables: effective precipitation ($P - Ep$), and the frequency of thunderstorms. The relationships indicate that decreased effective precipitation and increased thunderstorm activity lead to increases in both the number of fires and the total area burned by these fires.

Three spatial scales were considered in this study: the southwestern United States, the contiguous United States, and the entire Northern Hemisphere. Although we are not confident that the relationships developed with data from the southwestern United States can be used in other locations, we feel that the overall trends of the relationships are valid and robust. All three spatial scales are likely to experience increased lightning fire activity in a warmer climate. All results imply more fires, larger areas burned, and longer fire seasons. Results obtained using the GISS GCM indicate a possible increase in lightning-caused fires in the United States of 44% for a $2 \times CO_2$ climate, with a 78% increase in the area burned by these fires.

One of the most significant results of this study is that unlike today, where few lightning fires occur in the Tropics, future climate change could potentially result in large increases in tropical lightning fires. Considering the major extent of the damage caused by recent tropical fires during drought years (Malingreau et al. 1985), the situation in the future could become highly explosive. A more in-depth analysis of this result would factor in projected anthropogenic deforestation and land use.

Finally, changes in fire frequency and intensity need to be factored into estimates of future climate change due to their potential for altering the atmospheric concentrations of trace gases and aerosol particles as well as changing vegetation and surface albedo.

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